

**U.S. ENVIRONMENTAL PROTECTION AGENCY, REGION 6
FINAL ETHYLENE DIBROMIDE REMEDIATION SYSTEMS EVALUATION AT
FOUR SITES**

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Table of Contents

Executive Summary.....	ES-1
1.0 Introduction.....	1-1
1.1 Purpose and Objectives	1-1
1.2 Background	1-1
1.2.1 Historical Use of Ethylene Dibromide.....	1-3
1.2.2 Ethylene Dibromide Fate and Transport Summary	1-4
1.3 Research Methodology.....	1-8
2.0 Massachusetts Military Reservation	2-1
2.1 MMR Background.....	2-1
2.2 EDB Concentrations in Contaminated Media.....	2-3
2.3 Remediation Technologies Used.....	2-4
2.3.1 Effectiveness of Remediation Technologies.....	2-12
2.3.2 Costs of Remediation Technologies	2-17
2.3.3 Cleanup Status/Results.....	2-18
2.3.4 Problems Encountered	2-19
3.0 Home Oil.....	3-1
3.1 Home Oil Background	3-1
3.2 EDB Concentrations in Contaminated Media.....	3-3
3.3 Remediation Technologies Used.....	3-4
3.3.1 Effectiveness of Remediation Technologies.....	3-6
3.3.2 Costs of Remediation Technologies	3-10
3.3.3 Cleanup Status/Results.....	3-11
3.3.1 Problems Encountered	3-11
4.0 Del Monte	4-15
4.1 Del Monte Background	4-15
4.2 EDB Concentrations in Contaminated Media.....	4-18
4.3 Remediation Technologies Used.....	4-19
4.3.1 Effectiveness of Remediation Technologies.....	4-25
4.3.2 Costs of Remediation Technologies (if available).....	4-26
4.3.3 Cleanup Status/Results.....	4-26
4.3.4 Problems Encountered	4-27
5.0 Hastings Groundwater OU6.....	5-1
5.1 Hastings Background	5-1

5.2	EDB Concentrations in Contaminated Media.....	5-3
5.3	Remediation Technologies Used.....	5-5
5.3.1	Effectiveness of Remediation Technologies.....	5-12
5.3.2	Costs of Remediation Technologies (if available).....	5-15
5.3.1	Cleanup Status/Results.....	5-16
5.3.2	Problems Encountered	5-17
6.0	Research Findings and Conclusions	6-1
6.1	General Design Considerations and Constraints for Evaluated Remediation Systems	6-2
6.1.1	Air Sparging.....	6-2
6.1.2	Soil Vapor Extraction	6-3
6.1.3	Bioaugmentation/Biostimulation – Reductive Dehalogenation	6-3
6.1.4	Groundwater Extraction and Treatment.....	6-4
6.1.5	Monitored Natural Attenuation.....	6-4
6.2	Site Implementation of EDB Remediation Systems	6-5
6.2.1	Extraction, Treatment, and Discharge/Re-Injection	6-5
6.2.2	Air Sparging/SVE for Groundwater Treatment.....	6-12
6.2.3	Air Sparging/SVE for Source Treatment.....	6-12
6.2.4	SVE Air Treatment	6-14
6.2.5	Bioaugmentation/Biostimulation	6-14
6.2.6	Wellhead Protection.....	6-14
6.2.7	Monitored Natural Attenuation.....	6-15
6.2.8	Source Excavation	6-15
6.2.9	Low Permeability Cap	6-16
6.3	Conclusions	6-16
6.3.1	Overall Protection of Human Health and the Environment.....	6-16
6.3.2	Achievement of Cleanup Objectives	6-20
6.3.3	Remediation to Reduce/Eliminate Further Release	6-20
6.3.4	Long-Term Effectiveness.....	6-20
6.3.5	Short-term Effectiveness.....	6-20
6.3.6	Toxicity, Mobility, and Volume Reduction.....	6-21
6.3.7	Implementability	6-21
6.3.8	Costs.....	6-22
6.3.9	Community and Other Regulatory Agency Acceptance.....	6-23
7.0	References.....	7-1

List of Tables

Table ES-1. Comparative Summary of the Four Sites Reviewed.....	ES-3
Table 1-1. Physical and Chemical Properties	1-5
Table 2-1. EDB Concentrations at MMR.....	2-4
Table 3-1. Concentrations of EDB in Site Monitoring Wells from 1995 to 2013.....	3-3
Table 3-2. EPA Split Sample Results for EDB June and September 2009.....	3-4
Table 3-3. Concentrations of EDB in KDHE Water Plan Monitoring Wells, 2010-2013	3-4
Table 3-4. Types of Monitoring and AS/SVE Wells Installed for the Home Oil Company Bulk Plant Remediation.....	3-7
Table 5-1. Estimated and Actual Costs of Remediation Activities	5-16
Table 5-2. Breakdown of Cost Estimates for the SAEB Remedy	5-17
Table 6-1. Summary of Remediation Systems Evaluated.....	6-1
Table 6-2. Summary of Remediation Technologies	6-7

List of Figures

Figure 1-1. Site Map	1-2
Figure 1-2. General Conceptual Site Model for a Petroleum Spill/Release.....	1-8
Figure 2-1. FS-1 Treatment Process Flow Diagram Pre-2002 Fire	2-5
Figure 2-2. Current FS-1 Treatment Process Flow Diagram	2-7
Figure 2-3. Original FS-12 Treatment Process Flow Diagram	2-9
Figure 2-4. Reconfigured FS-12 Treatment Process Flow Diagram	2-9
Figure 2-5. FS-1 Extraction Well and Plant Influent Data (2003 – 2011).....	2-12
Figure 2-6. FS-1 Plume Boundary in 2002 and 2007	2-13
Figure 2-7. FS-12 Plume Boundary in 2002 and 2007	2-14
Figure 2-8. Changes in FS-12 Plume Boundary and Concentrations 1996 – 2004.....	2-14
Figure 2-9. FS-28 Plume Boundary in 2002 and 2007	2-15
Figure 2-10. FS-29 Plume Boundary in 2002 and 2007	2-16
Figure 3-1. Initial Soil Borings and Monitoring Wells	3-2
Figure 3-2. Diagram of AS/SVE Remediation Wells	3-7
Figure 3-3. AS/SVE Remediation Phase I	3-8
Figure 3-4. Remediation System Piping Plan.....	3-8
Figure 3-5. Shallow SVE Wells Radii of Influence.....	3-9
Figure 3-6. Deep SVE Wells Radii of Influence	3-9
Figure 3-7. EDB Concentration in Home Oil Plume 1996-2010	3-9
Figure 3-8. Emergency Response and Remedial Design Costs for the Home Oil Bulk Plant .	3-10
Figure 3-9. Breakdown of Costs for Remediation from 1999 to 2012	3-11
Figure 3-10. EDB Concentrations in Home Oil Monitoring Wells 1995 to 2013.....	3-13
Figure 4-1. Perched Groundwater Extraction Wells.....	4-21
Figure 4-2. Perched Aquifer Treatment System Pad	4-22
Figure 4-3. SVE Blowers and Carbon Treatment Vessel System	4-23
Figure 5-1. Cross-section of the Aquifer Underlying the FAR-MAR-CO Subsite	5-3
Figure 5-2. SVE Well and Blower Diagram.....	5-6

Figure 5-3. Emulsified Vegetable Oil Injection Locations	5-11
Figure 5-4. Amount of EDB Removed from Well, 1997 - 2010.....	5-13
Figure 6-1. EDB Remediation Timelines.....	6-17

Appendices

Appendix A: Maps for the Massachusetts Military Reserve Site

Appendix B: Maps for the Del Monte Site

Appendix C: Maps for the Hastings OU6 Site

Appendix D: General Information for Air Sparging Technology

Chapter VII Air Sparging - US Environmental Protection Agency

www.epa.gov/oust/pubs/tum_ch7.pdf

Appendix E: General Information for Soil Vapor Extraction Technology

Soil Vapor Extraction (PDF) - US Environmental Protection Agency

www.epa.gov/oust/pubs/tum_ch2.pdf

Appendix F: General Information for Reductive Dehalogenation

In Situ Bioremediation of Chlorinated Ethene: DNAPL Source Zones

The Interstate Technology & Regulatory Council, 2008

Introduction to Phytoremediation

EPA/600/R-99/107, 2000

Appendix G: General Information for Groundwater Extraction and Treatment Technology

Basics of Pump-and-Treat Ground-Water Remediation Technology

EPA/600/8-90/003, 1990

Appendix H: General Information for Monitored Natural Attenuation

A Guide for Assessing Biodegradation and source Identification of Organic

Ground Water Contaminations using Compound Specific Isotope Analysis (CSIA)

EPA 600/R-08/148, 2008

Monitored Natural Attenuation (PDF) - US Environmental Protection ...

www.epa.gov/oust/pubs/tum_ch9.pdf

Performance Monitoring of MNA Remedies for VOCs in Ground Water

EPA/600/R-04/027, 2004

List of Acronyms and Abbreviations

AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence (former name)
AFCEC	Air Force Civil Engineer Center
AOC	Administrative Order on Consent
ARAR	applicable or relevant and appropriate requirement
AS	air sparge
atm-m ³ /mol	atmosphere-cubic meter/mole
avgas	aviation gasoline
BCF	bioconcentration factor
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylenes
cat-ox	catalytic oxidation
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
cm/sec	centimeters per second
COC	contaminant of concern
COPC	contaminant of potential concern
CSM	conceptual site model
CT	carbon tetrachloride
CWSW	Coonamessett Water Supply Well
DBCP	dibromochloropropane
DCA	dichloroethane
DCE	dichloroethene
DCP	dichloropropane
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen
DPT	direct push technology
EDB	ethylene dibromide
EE/CA	engineering evaluation/cost analysis
EPA	United States Environmental Protection Agency
ETD	extraction, treatment, and discharge
ETR	extraction, treatment, and reinjection
EVO	emulsified vegetable oil
FS	feasibility study
FS-#	Fuel Spill, as in FS-1
HDOH	Hawaii Department of Health
HHE	human health and the environment
GAC	granular activated carbon
gpm	gallons per minute;
HDOH	Hawaii Department of Health
JP-4	Jet Propulsion Fuel-4
KDHE	Kansas Department of Health and Environment
Kg	kilogram
K _{oc}	organic carbon/water partition coefficient

KVA	Kunia Village Area
LNAPL	light non-aqueous phase liquid
MCL	maximum contaminant level
MDL	method detection limit
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
MMCL	Massachusetts maximum contaminant level
mm-Hg	millimeters of mercury
MMR	Massachusetts Military Reserve
MNA	monitored natural attenuation
MPP	Mashpee Pitted Plain
MSDS	material safety data sheet
msl	mean sea level
MTBE	methyl tertiary butyl ether
MW-	Monitoring Well-[identification number]
ND	not detected (or non-detect)
NMED	New Mexico Environment Department
NPL	National Priorities List
O&M	operations and maintenance
OU	operable unit
PAH	polynuclear aromatic hydrocarbons
PCE	tetrachloroethene
P.G.	Professional Geologist
ppb	parts per billion
PRG	Preliminary Remediation Goal
PRP	potentially responsible party
psi	pound per square foot
PVC	polyvinyl chloride
PWS	public water supply
RAO	remedial action objective
RCRA	Resource Conservation and Recovery Act
redox	reduction/oxidation
RI	remedial investigation
ROD	Record of Decision
ROI	radius of influence
RSL	Regional Screening Level
SAEB	source area enhanced bioremediation
SI	site investigation
SVE	soil vapor extraction
SVOC	semi-volatile organic compound
SWL	static water level
SWP	shallow well points
TCA	trichloroethane
TCE	trichloroethene
TCP	trichloropropane
TPH	total petroleum hydrocarbons

UST	underground storage tank
VOC	volatile organic compound
WEC	Whelan Energy Center
°C	degrees Celsius
µg/kg	micrograms per kilogram
µg/L	micrograms per liter
%	percent

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EXECUTIVE SUMMARY

Ethylene dibromide (EDB) contamination and remediation technologies were reviewed at four sites in order to determine what types of remediation had been successfully implemented and gather lessons learned from the applications. Remediation techniques succeeded in protecting human health and the environment at all four sites. The sites have achieved varying levels of compliance with the maximum concentration limit (MCL) of 0.05 micrograms per liter ($\mu\text{g/L}$) for EDB, but it appears that over time, all the sites will ultimately achieve this remediation goal. Table ES-1 provides a brief comparative summary of the four sites.

The Massachusetts Military Reservation (MMR) is a large military site with multiple fuel-spill groundwater plumes of various sizes and types. Four plumes required remediation for EDB, with an estimated contaminated volume of over 4 billion gallons of groundwater. The plumes continue to be treated by extracting groundwater and pumping it through granular activated carbon (GAC) vessels to remove EDB, then returning the treated water to the aquifer by re-injection or discharge to surface waters. EDB concentration profiles have continuously improved since beginning remediation, and key receptors including a local drinking water well have been protected from contamination. Cleanup efforts for these plumes are expected to last an additional 10 to 20 years.

The Home Oil site in Kansas remediated a single fuel-spill plume that threatened drinking water supplies. Their remediation included soil vapor extraction (SVE) with air sparging to eliminate the EDB source as well as groundwater extraction and treatment. The EDB concentrations in the plume have recently been found below the MCL of 0.05 $\mu\text{g/L}$, but treatment continues for other contaminants found in the groundwater.

The Hastings groundwater site in Nebraska includes multiple contaminated plumes that threaten drinking water. The EDB plume that was remediated originated from agricultural use of EDB as a fumigant and pesticide. Initial remediation efforts included treatment of the source area with SVE and extracting contaminated groundwater for use in industrial processes. *In situ* source area enhanced bioremediation treatment using injected vegetable oil was completed in 2010 to accelerate the degradation of residual contamination. The remediation efforts are nearing conclusion as many of the monitoring wells are now reporting near or below the MCL of 0.05 $\mu\text{g/L}$.

The Del Monte site in Hawaii includes contaminated soil, shallow groundwater, and deep groundwater from agricultural use and at least one spill of EDB. Remediation efforts included soil excavation, a protective cap over the source area, perched (shallow) groundwater extraction and treatment with *ex situ* phytoremediation, and basal (deep) groundwater extraction and treatment with air stripping and GAC. Remediation efforts have prevented the spread of contaminated basal groundwater, but concentrations have not yet reached the MCL of 0.05 $\mu\text{g/L}$. Remediation is ongoing and is expected to require an additional 10 to 20 years to meet all remediation objectives.

The four sites demonstrate a range of effective techniques for EDB remediation, but all of the sites required extraction of contaminated groundwater followed by some kind of treatment to remove EDB. Treatment of extracted groundwater was most often accomplished through the use

of GAC, whether as a primary or polishing (secondary) treatment method. Other key elements from the four sites include:

- Monitored natural attenuation (MNA) was not selected as a remediation alternative at any of the sites because it would not succeed in timely protection of human health and the environment, but was included as a component of the remediation alternative for Del Monte.
- Removal of the contamination source was critical in successfully achieving long term remediation goals. When an EDB source remained present (as it did in Home Oil and Del Monte), groundwater extraction could stop the spread of the EDB plume but could not reduce concentrations to the MCL.
- Remediation techniques had to be adjusted to adapt to local conditions, and frequently, mid-course corrections were required to optimize EDB removal.
- Remediation costs were highly variable depending on the site conditions, the concentrations and size of the EDB plume, the presence or absence of existing extraction wells, and many other variables.
- Achieving the MCL of 0.05 µg/L requires long times (more than 10 years) and treatment of extremely large volumes of water (billions of gallons).
- Wellhead protection, such as at MMR and Home Oil, was effective short term protection of water supplies for receptors.

Table ES-1. Comparative Summary of the Four Sites Reviewed

Characteristic	MMR	Home Oil	Del Monte	Hastings OU6
Spill Source/Cause	Leaking fuel lines and tanks and spills during operations	Leaking fuel UST	EDB spill and use as a fumigant	EDB spill and use as a fumigant
Spill Volume	70,000 gallons plus others-unknown sources; multiple plumes	Unknown	495 gal EDB	Spill volume not found in research to date; 500 ft. X 2000 ft.; plume extends > 2miles downgradient
Maximum EDB Concentration in Groundwater	890 µg/L	115 µg/L	3,227 µg/L (perched aquifer) 0.26 µg/L (basal aquifer)	511 µg/L
Depth to Groundwater (feet bgs)	>100 feet	125-130 feet	Perched: shallow to ~100 feet Basal: 850 feet	110-135 feet
Source Reduction Implemented	None	Air Sparge/SVE	Source (soil) excavation SVE	SVE
Remediation Technologies Implemented	Groundwater ETD/ETR	Air Sparge/SVE	Source (soil) excavation and cap Groundwater ETD ¹ MNA	ETD ² SVE Bioaugmentation
Time Estimated to Remediate	20 to 50 years	10 to 25 years	20 to 40 years	45 to 50 years

1 – extracted water from the perched aquifer was treated in a closed-loop ex situ phytoremediation treatment, so all water was evaporated and evapotranspired to eliminate any release

2 – water used in industrial processes

bgs – below ground surface

EDB – ethylene dibromide

ETD – extraction, treatment, and discharge to surface waters

ETR – extraction, treatment, and re-injection to groundwater

MMR – Massachusetts Military Reservation

MNA – monitored natural attenuation

OU – Operable Unit

SVE – soil vapor extraction

UST – underground storage tank

µg/L – micrograms per liter

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1.0 INTRODUCTION

This draft report presents information concerning selection evaluation, design, construction, operation and maintenance (O&M), efficiency, challenges, and cost for remediation systems used at four facilities to remediate ethylene dibromide (EDB) contamination in soils and groundwater. This report details the findings from the evaluated remediation systems at the four sites, which include (1) the Massachusetts Military Reservation (MMR), which includes evaluation of four distinct EDB-contaminated plumes; (2) Home Oil Company Bulk Plant in Selden, Kansas; (3) the Del Monte site in Honolulu County, Oahu, Hawaii; and (4) Hastings Ground Water Contamination Superfund Site, Operable Unit (OU) 6, in Hastings, Nebraska. Figure 1-1 depicts the location of each of the four sites evaluated.

This report is the second deliverable under Task Order 6606, Contract No. EP-W-12-032, and will be used by U.S. Environmental Protection Agency (EPA) Region 6 to evaluate the EDB remediation systems for eventual presentation to New Mexico Environment Department (NMED) in Albuquerque.

1.1 PURPOSE AND OBJECTIVES

EDB has often been ignored at other fuel release sites undergoing investigation and characterization because other risk-drivers from fuel spills, such as benzene, toluene, ethylbenzene, and total xylenes (BTEX), have been targeted instead. Consequently, experience with EDB remediation at fuel spills is more limited than for other risk drivers. Researching remediation of EDB sites will provide EPA with an understanding of the success and challenges associated with EDB remediation to help prepare for the presentation to NMED.

The purpose of this report is therefore to identify potential remediation systems for EDB contamination in the groundwater as well as for the contaminant source in the vadose zone and to evaluate remedy selection criteria, effectiveness, design and construction limitations/constraints, O&M requirements, and general costs. The objective is to provide EPA and NMED with information to begin effectively evaluating remediation systems and plan for further site characterization to collect data necessary to fully evaluate remedy selection.

1.2 BACKGROUND

Premature ignition during operation of an internal combustion engine, which causes overheating, loss of power and efficiency, and potential engine damage when extreme, required addition of tetraethyl lead prior to development of other solutions (Seyferth 2003, Henderson et al 2009). However, combustion of fuel with tetraethyl lead formed solid lead deposits on valves and spark plugs (Henderson et al 2009). EDB and 1,2-dichloroethane (1,2-DCA), which is not a subject of this report, were added to gasoline because they form volatile lead halides exhausted from an engine as gases to avoid lead deposit formation inside the engine. These compounds were included in virtually all leaded gasoline sold, and are commonly referred to as “lead-scavengers” (Henderson et al 2009). As discussed further in Section 1.2.1, these lead scavengers are no longer part of most fuels sold in the U.S. today, although EDB remains an additive in off-road fuels and aviation gasoline (avgas).

Figure 1-1. Site Map



Petroleum fuels are a complex mixture of hundreds of compounds, including alkanes, alkenes, polynuclear aromatic hydrocarbons (PAHs), and other organic compounds. For example, the typical composition of gasoline hydrocarbons by percent volume is approximately 4-8 percent (%) alkanes; 2-5% alkenes; 25-40% isoalkanes; 3-7% cycloalkanes; 1-4% cycloalkenes; and 20-50% total aromatics (e.g., 0.5-2.5% benzene) (ATSDR 2013). EDB in a petroleum-based fuel, such as avgas, comprises less than 1 percent of the fuel by mass based on reviews of available material safety data sheets (MSDSs).

Once released to groundwater, the physical properties of EDB and 1,2-DCA suggest they will be mobile. EDB is a moderately soluble compound, with an aqueous solubility of 4,300 milligrams per liter (mg/L) (Montgomery 1997); the solubility of 1,2-DCA is 8,500 mg/L (Bedient et al. 1999). Based upon these solubilities and their gasoline–water partition constants, dissolved phase EDB and 1,2-DCA concentrations up to 1,900 and 3,700 micrograms per liter (µg/L) can be expected in groundwater near the source area of a leaded gasoline release (Falta 2004). Both EDB and 1,2-DCA have low air–water, soil–water and octanol–water partition constants, so they will not partition out of groundwater into air and soil to any great degree. These factors indicate lead scavengers could form dissolved phase plumes downgradient of the release source zone.

Historically, USEPA and state regulatory programs have required that a small number of organic contaminants be analyzed during fuel release and spill investigations, notwithstanding gasoline is a complex mixture of hundreds of hydrocarbons. These identified contaminants of potential concern (COPCs) are typically selected for investigation because they are considered risk-drivers for protection of human and ecological receptors for both potential groundwater exposure and soil exposure. These COPCs typically include BTEX, methyl tertiary butyl ether (MTBE), and several PAHs (e.g., benzo(a)pyrene). Risk-based cleanup criteria, such as maximum contaminant levels (MCLs) for groundwater (40 Code of Federal Regulations (CFR) Part 141, Subpart G) and USEPA Regional Screening Levels (USEPA 2012d), New Mexico Environment Department (NMED) Soil Screening Levels (NMED 2006), etc., are typically used to screen a site for and then to evaluate potential risk from these COPCs. Often, EDB is overlooked as a COPC even though the risk-based criterion for EDB (i.e., its MCL) is only 0.05 µg/L in groundwater while the MCL for benzene is 5.0 µg/L, or more than two orders of magnitude greater than the MCL for EDB. In fact, EDB has lowest federal MCL for any compound except dioxin. Reasons for historically overlooking EDB as a COPC may include that analytical methods used during site investigations did not have detection limits low enough to detect EDB, or the expectation that EDB would have naturally attenuated in groundwater since the time that EDB use in most fuels as a lead scavenger was stopped, or that EDB concentrations in fuels were much lower than the other risk-drivers (e.g., benzene), or simply that remediation and/or risk management of the other risk-drivers would be adequately protective regardless of residual EDB.

1.2.1 HISTORICAL USE OF ETHYLENE DIBROMIDE

EDB was widely used in agricultural applications as a pesticide and fumigant as well as a lead scavenger in leaded fuels, including avgas. EDB is also used as a chemical intermediate in

synthesis and as a nonflammable solvent for resins, gums, and waxes (USEPA 2006). The last registered garment fumigant containing EDB was Tri-X-Garment Fumigant. EDB was used as a pesticide on citrus crops, on vegetables, on grain crops, and to protect golf courses (USEPA 2006). In 1977 approximately 136 million kilograms of EDB were produced in the USA; 127 million kilograms were used in fuel, approximately 8 million kilograms were used as a soil fumigant, and approximately 0.9 million kilograms were used to fumigate stored grain and grain milling machinery, and quarantined citrus and other tropical fruits (USEPA 2006). Production of this fumigant was cancelled on September 8, 1993.

As introduced in Section 1.2, EDB was used as a lead-scavenger in petroleum fuels that historically used tetraethyl lead, which was used to mitigate pre-ignition issues for internal combustion engines (Seyferth 2003, Henderson et al 2009). Diminished use of tetraethyl lead and the consequent need for EDB as a lead-scavenger began in the 1970's as concern grew about the consequences of lead in vehicle emissions (Seyferth 2003). USEPA regulation of vehicle emissions also induced development of the catalytic converter to destroy nitrogen oxides, carbon monoxide, and hydrocarbons in the exhaust gas. A catalytic converter uses noble metal oxidation catalysts to do this, and studies showed that EDB decreases catalyst activity and that tetraethyl lead causes permanent destruction of the catalyst (Seyferth 2003). An increasing number of automobiles were built with catalytic converters in the 1970's that therefore could not tolerate leaded gasoline. The government-mandated reduction in the lead content of leaded gasoline for protection of human health and the environment and the introduction of the catalytic converter were responsible for the drastic decline in EDB in petroleum fuels.

Use of EDB in leaded fuels decreased through the 1970's and 1980's before ceasing almost entirely in approximately 1987; however, lead scavengers are still used today in off-road fuels (e.g., racing fuels) and avgas (Aronson and Howard 2008). Recent studies demonstrate that lead scavengers may persist for long periods of time in certain ground water environments as detailed in Section 1.2.2. Although lead and lead scavengers were phased out in conventional motor gasoline by the end of the 1980s, the lead scavengers from old releases may continue to contaminate ground water at many gasoline service station sites. In addition, more recent spills and releases may also provide a fresher source of groundwater contamination from avgas and off-road fuels that still contain lead scavengers.

1.2.2 ETHYLENE DIBROMIDE FATE AND TRANSPORT SUMMARY

The rate of attenuation of EDB in groundwater within the source area of a release is controlled by the rate of attenuation in the contaminated soils (i.e., the source), the rate at which EDB dissolves from the residual fuel into the groundwater, dispersion in the aquifer, sorption to native organic matter, biodegradation by aerobic or anaerobic microorganisms, or by abiotic processes including neutral hydrolysis and non-biological reactions with either sulfide in solution or with sulfide minerals. The rate of attenuation in soils contaminated with residual fuel determines how long a release of gasoline can continue to contaminate groundwater. The rate of removal in the groundwater will determine how far the plume of contamination can reach.

The physical and chemical properties of EDB, which are summarized in Table 1-1 along with benzene and MTBE as other common risk drivers in fuel releases, provide insight to the general behavior of EDB dissolved in groundwater and include:

- Low to moderate sorptive affinity for aquifer media, so dissolved EDB tends to remain dissolved and mobile in the groundwater;
- Relatively volatile;
- Biodegrades under both aerobic and anaerobic conditions;
- Biodegrades more rapidly anaerobically (half-life of 15 to 50 days) than aerobically (half-life of 35 to 360 days); and
- Tends not to bioconcentrate or bioaccumulate in food chains.

(USEPA 2006)

Table 1-1. Physical and Chemical Properties

Chemical	Specific Gravity <1.0 = LNAPL >1.0 = DNAPL	Water Solubility (mg/L) Higher value indicates greater propensity to dissolve into groundwater	Vapor Pressure (mm Hg at 25°C) Higher value indicates higher propensity to volatilize to air	Log K _{oc} Lower value lower propensity to bind to soil and greater mobility in groundwater
EDB	2.17	4,200	11	1.45
Benzene ¹	0.88	1,780	76 – 95.2	1.5 - 2.16
MTBE ¹	0.74	43,000 – 54,300	245 - 256	1.0 – 1.1

(Source: USEPA 2006)

1 – for comparison of relative values
DNAPL – dense non-aqueous phase liquid
K_{oc} – soil organic carbon/water partition coefficient
LNAPL – light non-aqueous phase liquid
mg/L – milligrams per liter
mm Hg – millimeters mercury
MTBE – methyl tert-butyl ether

Following are some general characteristics for the fate of EDB in the environment:

- If released to air, a vapor pressure of 11.2 millimeters of mercury (mm Hg) at 25 degrees Celcius (°C) indicates EDB will exist solely as a vapor in the ambient atmosphere.

- Vapor-phase EDB will be degraded in the atmosphere by reaction with photochemically-produced hydroxyl radicals. The half-life for this reaction in air is estimated to be 64 days.
 - EDB is not expected to undergo direct photolysis in the ambient atmosphere.
- If released to soil, EDB is expected to have high to very high mobility based upon a log soil organic carbon/water partition coefficient (log K_{oc}) value of approximately 1.45.
 - Volatilization from moist soil surfaces is expected to be an important fate process based upon a Henry's Law constant of $6.5E-04$ atmosphere-cubic meter/mole ($\text{atm}\cdot\text{m}^3/\text{mol}$).
 - EDB may volatilize from dry soil surfaces based upon its vapor pressure.
 - Biodegradation in soil is expected to be an important fate process; half-lives ranging from 1.5 to 18 weeks were determined in one laboratory screening study using 100 soils.
- If released into water, EDB is expected to be mobile.
 - EDB is not expected to adsorb to suspended solids and sediment based upon the log K_{oc} values.
 - Microbial degradation of EDB was examined in microcosms using shallow aquifer material and groundwater; EDB degraded aerobically in all samples with half-lives ranging from 35 to 350 days.
 - Volatilization from water surfaces is expected to be an important fate process based upon this compound's Henry's Law constant. Estimated volatilization half-lives for a model river and model lake are 2.6 hours and 6.0 days, respectively.
 - Bioconcentration factors (BCFs) ranging from <1 to 14.9 suggest that propensity for EDB to bioconcentrate in aquatic organisms is low.
 - Uncatalyzed hydrolysis is comparatively slow with an estimated half-life of approximately six years at 25°C , but hydrolysis catalyzed by the presence of various natural substances (such as the hydrogen sulfide ion) may be competitive with biodegradation with an estimated half-life of one to two months.

(NCBI 2004).

These general characteristics are only appropriate for use in initial evaluation of fate and transport for EDB. However, specific fate and transport characteristics for EDB rely not only on the chemical and physical properties of EDB, but also depend greatly on the site-specific conditions and characteristics of the media in which the EDB is migrating. For instance, studies have reported first order rate constants for biodegradation of EDB from laboratory studies that are reasonably consistent with rates determined from several available field scale rates (USEPA 2008). However, these rates were found to be inconsistent with rate constants for EDB

biodegradation at the MMR site in which the biodegradation rate was determined to be ten-fold to one hundred-fold slower than the rate observed at other sites (USEPA 2008). It was postulated that the difference in the biodegradation rate at MMR as compared to other sites could be attributed to the lack of strong reducing conditions in the aquifer that would be required to foster BTEX fermentation producing the hydrogen required for anaerobic biodegradation of EDB. Consequently, general fate and transport and even general laboratory bench testing cannot alone determine the most appropriate method of EDB remediation. Site-specific conditions and characteristics must be evaluated in concert with other available and pertinent studies and information for comprehensive evaluation of fate and transport of EDB.

EDB will initially migrate through the soil as part of the hydrocarbon matrix (i.e., with the mixture of over one hundred compounds in which EDB is dissolved). Many of the compounds in the petroleum have a higher affinity to adsorb to soil particles, but EDB has only limited propensity to adsorb (i.e., low log K_{oc} value) and therefore is more likely to continue to migrate downward toward the aquifer; it will also likely dissolve in any percolating precipitation migrating to the groundwater based on its relatively high solubility in water. Dissolved EDB in the water will directly enter the aquifer and is likely to remain highly mobile in the groundwater based on its low affinity to adsorb to organic carbon (i.e., low log K_{oc} value) and its high solubility.

Some EDB will likely remain as a source for groundwater contamination in the petroleum that migrates to the aquifer, which floats as a light non-aqueous phase liquid (LNAPL) and distributes within the smear zone immediately above the groundwater. Although EDB has a density greater than water and would by itself at concentrations greater its solubility in water sink as a dense non-aqueous phase liquid (DNAPL), EDB will remain dissolved in the petroleum floating on the groundwater and will continue to be a source of groundwater contamination as it dissolves into the water phase. This is particularly likely at the low concentrations used as an additive in petroleum fuels and also because it has weathered as it migrates through the vadose zone. So, a site with a substantial spill or release of fuel would likely be characterized by two primary zones: 1) the source zone, which is defined as the area of aquifer or vadose zone where the LNAPL is in contact with aquifer materials, and 2) the plume zone, where contamination is present in adsorbed and dissolved form in the aquifer.

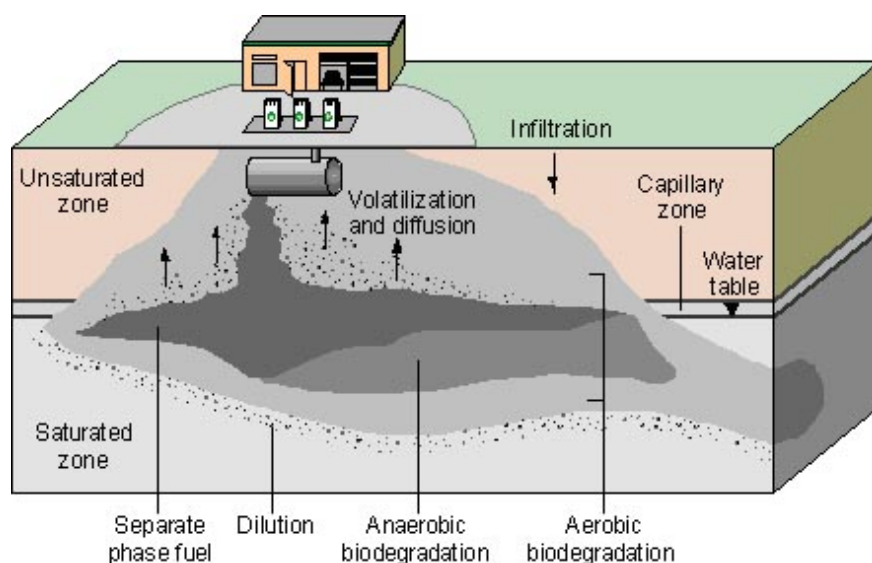
Attenuation of EDB in LNAPL and residual EDB contamination in the vadose zone and in the smear zone can be more rapid than for many other compounds in the petroleum. EDB's water solubility and its low affinity to adsorb to soil cause the EDB to migrate more rapidly with percolating water. As groundwater fluctuates into the smear zone, capillary fringe, and the LNAPL, EDB is flushed further into the system. Consequently, the source concentration for EDB may over time be less than the source concentrations for other compounds in the LNAPL.

As indicated above, EDB is comparatively mobile in the groundwater and often migrates ahead of many other soluble compounds leaching from the petroleum source. Attenuation is often evaluated in consideration of three spatial zones within the aquifer: (1) directly downgradient from the contamination source, which is characterized by high dissolved phase concentrations of EDB and BTEX; (2) further downgradient where dissolved phase concentrations decline by

orders of magnitude at varying distances downgradient from the source depending on site conditions; and (3) the far extent of the plume in which low concentrations (but above the MCL) of EDB and 1,2-DCA may exist. Both zones 1 and 2 are assumed to be anaerobic because available oxygen is depleted quickly by an abundance of fuel hydrocarbons undergoing aerobic biodegradation; some hydrocarbons can serve as electron donors in anaerobic dehalogenation processes of EDB (Suarez and Rifai 1999). BTEX compounds from the petroleum contamination may not be present in the far extent of the plume (Zone 3) because these compounds are more readily biodegraded in the more aerobic conditions in Zone 2 (Suarez and Rifa 1999). The far downgradient zone in Zone 3 is usually, although but not always, aerobic. The aerobic conditions are not ideal for reductive dehalogenation of chlorinated compounds, such as EDB.

Figure 1-2 depicts a general conceptual site model (CSM) for a typical petroleum spill or release.

Figure 1-2. General Conceptual Site Model for a Petroleum Spill/Release



(Source: CEPA 2013)

Based on the characteristics of EDB and its fate and transport, several remediation systems seem potentially appropriate, including: air sparging of groundwater with soil vapor extraction (SVE) for soil gases immediately above the aquifer; injection of a reducing agent (e.g., zero valent iron); injection of biostimulation agents to encourage reductive dehalogenation (bioaugmentation); pump and treat with granular activated carbon (GAC), and air stripping. Many of these, and other optional treatments such as phytoremediation, have been used for remediation of EDB as discussed in more detail in this report.

1.3 RESEARCH METHODOLOGY

The initial task was identification of sites contaminated with EDB that have remediation systems for which information is available. USEPA then selected four sites for detailed evaluation in this report. Potentially useful information initially evaluated during identification of sites included

the types of remediation technology, the alternatives available (e.g., the combination, design, construction, and O&M of technologies), the benefits and limitations/constraints of the technologies, rates of contaminant removal, costs, and other relevant factors (Toeroek 2013). The general approach to meet the purpose and objectives as presented in Section 1.2 is to consider the same remediation alternative evaluation criteria as would be considered in the selection process for a corrective measure or evaluation in a feasibility study under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).

EPA has established expectations for remedies that are not necessary binding requirements, but they are used to focus stakeholders on remedial alternatives that have the greatest likelihood of fulfilling the statutory and regulatory intent of the Resource Conservation and Recovery Act (RCRA) Corrective Action (USEPA 2000a). These EPA expectations include:

- use of treatment to address the principal threats posed by a site whenever practicable and cost-effective.
- return of usable groundwaters to their maximum beneficial uses wherever practicable, within a time frame that is reasonable given the particular circumstances of the site.
- use of engineering controls, such as containment, for wastes and contaminated media that can be reliably contained, pose relatively low long-term threats, or for which treatment is impracticable.
- use of a combination of methods (e.g., treatment, engineering and institutional controls), as appropriate, to achieve protection of human health and the environment.
- use of institutional controls such as water and land use restrictions primarily to supplement engineering controls as appropriate for short- and long-term management to prevent or limit exposure to hazardous wastes and constituents. EPA does not expect that institutional controls will often be the sole remedial action.
- consideration of using innovative technology when such technology offers the potential for comparable or superior treatment performance or implementability, less adverse impact, or lower costs for acceptable levels of performance when compared to more conventional technologies.
- remediation of contaminated soils as necessary to prevent or limit direct exposure of human and environmental receptors and prevent the transfer of unacceptable concentrations of contaminants (e.g., via leaching, runoff or air borne emissions) from soils, including subsurface soils, to other media.

The evaluation criteria specifically include the following (USEPA 2000b):

- protect human health and the environment based on reasonably anticipated land use(s), both now and in the future;
- achieve media cleanup objectives appropriate to the assumptions regarding current and reasonably anticipated land use(s) and current and potential beneficial uses of water resources; and
- remediate the sources of releases so as to eliminate or reduce further releases of hazardous wastes or hazardous constituents that may pose a threat to human health and

the environment, and using treatment to address principal threat wastes, unless alternative approaches are approved by the overseeing regulator.

Other considerations, which are similar to those considerations evaluated in a feasibility study (FS) under CERCLA include: (1) Long-Term Effectiveness, in which remedies are evaluated based on the long-term reliability and effectiveness they provide and the degree of certainty that they will remain protective of human health and the environment; (2) Toxicity, Mobility, and Volume Reduction, in which remedies are evaluated based on the degree to which they employ treatment that reduces the toxicity, mobility or volume of hazardous wastes and hazardous constituents; (3) Short-term Effectiveness, in which remedies are evaluated based on the short-term effectiveness and risks posed and the amount of time it will take for remedy design, construction, and implementation; (4) Implementability, in which remedies are evaluated based on the effort and the technical and administrative feasibility and availability of services to design, gain approvals and permits, construct, O&M, and monitor the remedy; (5) Costs, in which remedies are evaluated for total present value costs including all capital, O&M, and long-term monitoring until remedial action objectives are met; and (6) community and other regulatory agency acceptance of the remedy (USEPA 2000b).

With these EPA objectives and evaluation criteria in mind, the remediation systems at the four sites were reviewed and evaluated using available online documents, documents requested from representatives at the four sites, and interviews with persons knowledgeable of the sites and the construction and O&M of the remediation systems.

2.0 MASSACHUSETTS MILITARY RESERVATION

2.1 MMR BACKGROUND

MMR is located on Cape Cod, MA, on 20,000 acres of land that is part of the towns of Sandwich, Bourne, Falmouth, and Mashpee. Used as a training camp by the U.S. Army and Air Force since 1935, most of the industrial activities associated with military use were located in the southern portions of the reservation. These activities included aircraft runways, aircraft and vehicle maintenance areas, landfills, and firefighter training facilities. The most intense use of the base took place between 1940 and 1946 by the U.S. Army, and from 1955 to 1972 by the U.S. Air Force. The use of petroleum products and other hazardous materials was greatest during these times, as was the generation of hazardous wastes (Cape Cod Commission 1998).

In 1989, the MMR was added to EPA's National Priority List (NPL) (under CERCLA) after several groundwater contamination plumes were discovered in the prior years. Approximately 65 billion gallons of groundwater were thought to be contaminated near MMR. Contaminants, in addition to EDB, discovered in the groundwater across the entire MMR facility include solvents and their break-down products, such as tetrachloroethene (PCE), trichloroethene (TCE), and 1,1,2-trichloroethane (TCA); metals; contaminants associated with explosives, such as perchlorate and nitrotoluenes; and petroleum contaminants, such as benzene and toluene. EDB is the primary contaminant of concern in four "fuel spill" (FS) plumes evaluated herein totaling approximately 10 billion gallons of contaminated water (Cape Cod Commission 1998; AFCEE 2010). As of 2011, the Air Force had spent a total of \$660 million on cleanup at MMR, which includes multiple other plumes and sources of contamination, and expects to spend an additional \$850 million by the time remediation is expected to be completed midway through the 21st century (Brennan 2011). See Section 2.3.2 of this report, Costs of Remediation Technologies, for the approximate costs associated with the remediation technology used at the four EDB plume sites.

Site Geology/Hydrogeology

The regional geology of western Cape Cod is composed of glacial sediments deposited during the retreat of the Wisconsin stage of glaciation between 7,000 and 85,000 years ago. The regional geology is dominated by three extensive sedimentary units: Buzzards Bay moraine, Sandwich moraine, and the Mashpee Pitted Plain (MPP), which consists of poorly sorted, fine to coarse-grained sands forming a broad outwash plain. Underlying MPP are fine-grained, glaciolacustrine sediments and basal till at the base of the unconsolidated sediments. The portion of the overburden composed of MPP outwash sediments varies in thickness from approximately 225 feet near the moraines in the north to about 80 feet near the shore of Nantucket Sound. Glaciolacustrine sediments and till underlying MPP generally increase in thickness as the proportion of MPP sediments decreases. Bedrock, which has been mapped as a granodiorite, lies approximately 300 feet below ground surface (bgs) (HWRAP 2000).

The aquifer underlying MMR is designated as a sole-source aquifer by EPA. Depth to groundwater is generally greater than 150 feet bgs and aquifer recharge occurs from precipitation

(Jacobs 2005). The aquifer is composed of unconsolidated sediments consisting of the MPP and finer-grained till and lacustrine sediments (HWRAP 2000).

Summary of the Four FS Plumes

Appendix A, Map 1, shows the plumes locations (AFCEE 2010). A summary of the characteristics of each of the four plumes is below.

FS-1

The source of the FS-1 groundwater plume was the Aviation Gas Fuel Value Test Dump Site on the eastern part of MMR. The site was used from 1955 until 1970 to test fuel dump valves on aircraft, which involved the release of avgas directly to the ground (AFCEE 2010). FS-1 is a detached plume beginning 2,000 feet downgradient from the suspected source area (see Appendix A, Map 2). At its trailing edge, this detached plume is deep within the aquifer, but then rises abruptly and discharges to surface water in the Quashnet River cranberry bogs. The Quashnet River is fed by a controlled head gate located on the northeast corner of Johns Pond. From there, the river flows through the large cranberry bog adjacent to Johns Pond and onward to Waquoit Bay. The upper reaches of the Quashnet River are fed by groundwater discharge (HWRAP 2000).

A site investigation (SI) was performed in the source area in 1989. Explorations included 30 soil gas sampling points, one soil boring, and three monitoring wells. Fuel-related compounds were detected in groundwater above MCLs. An initial remedial investigation (RI) was performed in 1990 in which FS-1 was differentiated into two operable units: FS-1B source area and FS-1B downgradient groundwater. Seven source area wells were installed and two source area soil borings were completed. Twelve downgradient wells were installed in two well fences. Four additional water table wells were installed to aid in determination of local groundwater flow. Source area wells were found to contain fuel-related compounds. Of these, only toluene and lead were above MCLs. No significant concentrations of contaminants were found in the surface or subsurface soils at the FS-1 source area. Downgradient wells did, however, detect EDB at concentrations above MCLs, which became the impetus for the remediation of FS-1. The FS-1 Record of Decision (ROD), signed in April 2000, stated that since soils at the FS-1 source area would not cause continuing degradation of groundwater, no further action was needed there (HWRAP 2000).

FS-12

The source of the FS-12 groundwater plume was a series of releases from approximately 1969 through 1970 from a section of now-abandoned fuel pipeline that ran from the Cape Cod Canal to MMR (see Appendix A, Map 3). The operation of the pipeline was discontinued in 1973, and the underground fuel line was clean-closed in place in 1997. The pipeline carried avgas. In 1990 the plume was first detected when the Sandwich Water District performed some exploratory drilling for future municipal wells. In 1990 an expanded SI was conducted to characterize the nature and extent of the suspected groundwater contamination. The expanded SI included installation of groundwater monitoring wells and a soil gas survey. Based on findings of possible significant risk, the Air National Guard expanded the SI to an RI/FS (Jacobs 2006).

In January 1992 the FS-12 RI was initiated. As a result of modeling conducted for the RI, the FS-12 spill was estimated to be about 70,000 gallons of avgas. During the RI, free product was found above the water table. The free product was identified as a diesel-like fuel, very likely Jet Propulsion Fuel-4 (JP-4) with traces of other components that are more characteristic of gasoline-based fuel. The free product contained BTEX. No EDB was detected in the free product, but samples collected during the groundwater investigation contained high levels of EDB. The highest concentration detected during analysis of EDB was 597 µg/L (Jacobs 2006).

Groundwater sampling from 2011 indicates that some residual levels of fuel-related compounds still remain in the shallow groundwater beneath the source area, but not enough to sustain a groundwater plume. Groundwater concentrations in monitoring wells located in the source area no longer exceed MMCL and thus the plume is not delineated in the source area (CH2M Hill 2011).

FS-28

The FS-28 groundwater plume was first discovered in 1993. While there is no known source, it most likely migrated from the various vehicle maintenance shops, runways, and housing facilities that are located along the southern portion of MMR (AFCEE 2010). In 2000, the plume extended from the Crane Wildlife Management Area, under the western portion of Coonamessett Pond, and terminated in the cranberry bogs surrounding the Coonamessett River (see Appendix A, Map 4) (Jacobs 2000a).

FS-29

The FS-29 groundwater plume was first discovered in the late 1990s. As with FS-28, there is no known source for this plume, though it likely originated from the various vehicle maintenance shops, runways, and housing facilities that are located along the southern portion of MMR as well (AFCEE 2010). In addition to EDB, carbon tetrachloride (CT) is also a primary contaminant of concern (CH2M Hill et al., 2008). The FS-29 plume is over 9000 feet long, extending from the Crane Wildlife Management Area across Route 151. The maximum width of the plume, just south of Route 151, is approximately 1,300 feet. The plume comprises two lobes, the shallower one occurring from approximately 30 to 100 feet below mean sea level (msl), with an average thickness of 30 feet, and the deeper one occurring from approximately 120 to 220 feet below msl, with a thickness ranging from 30 to 50 feet (see Appendix A, Map 5) (Jacobs 2000a).

2.2 EDB CONCENTRATIONS IN CONTAMINATED MEDIA

Numerous investigations and ongoing sampling have occurred at the four EDB plumes at MMR over the last several decades. Table 2-1 summarizes these sampling events by showing the highest concentration of EDB in the groundwater in 2011, 2009, and the historic highest level, as well as the amount of contaminated water remaining as of the latest estimates. The Massachusetts maximum contaminant level (MMCL) for EDB is 0.02 µg/L. This is equivalent to about half a drop of EDB in an Olympic size swimming pool (AFCEE 2010).

Table 2-1. EDB Concentrations at MMR

Plume Name	Contaminated Water Remaining Above MMCL (gallons)	2011 Highest Level of EDB Contamination (µg/L)	2009 Highest Level of EDB Contamination (µg/L)	Highest Historic Level of EDB Contamination (µg/L)
FS-1	256 million (2006)	0.21	0.857	44.5 (October 2000)
FS-12	156 million (2011)	21.4	23.1	890 (November 1996)
FS-28	1.8 billion (2006)	1.1	1.38	18 (January 1997)
FS-29	1.2 billion (2000)	NA	0.084	0.318 (May 2001)

(Sources: AFCEE 2010; Jacobs 2000a; CH2M Hill 2012a; CH2M Hill 2012b; CH2M Hill 2012c)

EDB – ethylene dibromide

MMCL – Massachusetts maximum contaminant level

NA – not applicable

µg/L – micrograms per liter

2.3 REMEDIATION TECHNOLOGIES USED

The remedial action objective for all plumes at MMR is to prevent the risk of human exposure to EDB at concentrations above the MMCL, and restore the aquifer to its beneficial uses within a reasonable amount of time. The Air Force Civil Engineer Center (AFCEC, formerly the Air Force Center for Engineering and the Environment (AFCEE)) is overseeing the remediation of all four EDB plumes at MMR. All of the treatment plants at MMR, including those for FS-1, -12, -28, and -29, utilize the same general technology consisting of one or more “trains” of two, 20,000 pound, granular activated carbon (GAC) vessels. Each train consists of two vessels in a series. The first vessel, into which groundwater influent is introduced, is called the “lead” vessel (i.e., the primary treatment vessel). The second vessel, which receives effluent from the “lead” vessel, is called the “lag” vessel (i.e., the secondary or polishing treatment vessel) and serves as back-up if breakthrough of the lead GAC vessel occurs.

Within each treatment plant, the GAC media is replaced in the lead vessel when a contaminant is detected in the effluent, also known as a breakthrough from the lead vessel. If contamination is detected before the projected end of the GAC media’s life, a split sample from the lead vessel is analyzed within 24 hours at the onsite lab to confirm breakthrough. Should there be confirmation of breakthrough, a new bed of GAC is ordered to replace the carbon in the lead vessel. The GAC used at MMR is size 12x40 and is pH adjusted to prevent a pH spike upon change-out. Whenever a lead GAC needs to be changed, the GAC vessel arrangement is swapped, so the clean GAC is placed in the lag position and the former lag vessel is placed in the lead position (AFCEE/MMR 2011). The subsections below describe the specific treatment systems in place at each of the four FS plumes.

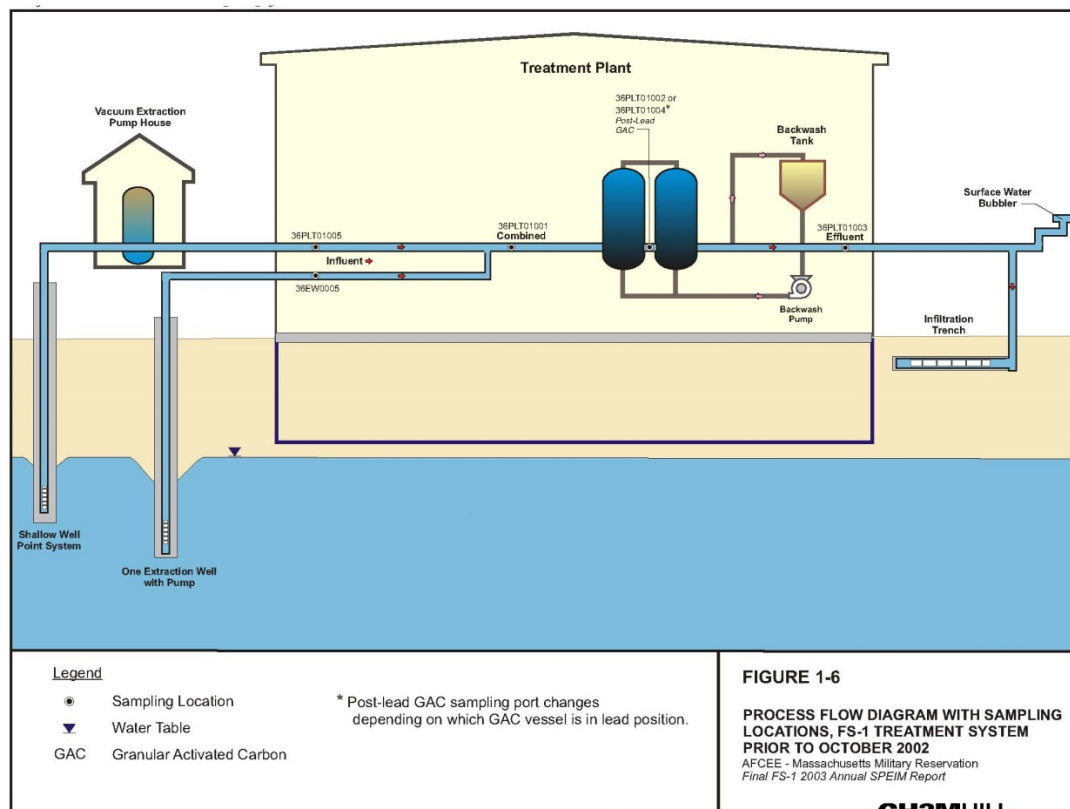
FS-1

A 1999 FS proposed four remediation alternatives that address nine CERCLA evaluation criteria, including implementability, effectiveness in reducing public exposure to contaminants, and cost among others. Alternative 1 was no action, which serves as a baseline from which to compare other alternatives and therefore includes no monitoring, treatment, or further evaluation.

Alternative 2 included only limited action and was determined to fail to meet the remedial action objectives (RAOs); therefore, it was excluded from further evaluation in the FS. Instead, Alternative 2B was developed to meet RAOs and called for limited action with the extraction and treatment of groundwater at just the leading edge of the plume and institutional controls to prevent usage of the aquifer during cleanup. Alternative 3 included groundwater extraction from wells oriented axially down the center of the plume, treatment of the extracted groundwater, and institutional controls to prevent usage of the aquifer during cleanup. Finally, Alternative 3B, the scenario chosen for implementation by the ROD, combines the plans of Alternatives 2B and 3 by including both leading edge and axial plume groundwater extraction, along with treatment, and institution controls to prevent usage of the aquifer during cleanup (HWRAP 2000).

AFCEE (now AFCEC) originally installed an extraction, treatment, and discharge (ETD) system as a pilot test in 1999, and this system extracted 750 gallons per minute (gpm) at the southern portion of the plume out of one extraction well constructed with a screened interval from -87 to -148 feet below msl and 175 shallow wellpoints with screened intervals from 7 to -180 feet msl (SWPs). Extracted water was treated using two GAC vessels. Treated water was then discharged to the aquifer using a 120 gpm shallow infiltration trench, and to the Quashnet River surface via a discharge “bubbler” system. The pilot system operated until October of 2002 when a fire destroyed the treatment plant (CH2M Hill 2004). The image below (Figure 2-1) shows the treatment process in place at FS-1 prior to the fire.

Figure 2-1. FS-1 Treatment Process Flow Diagram Pre-2002 Fire



(Source: CH2M Hill 2004).

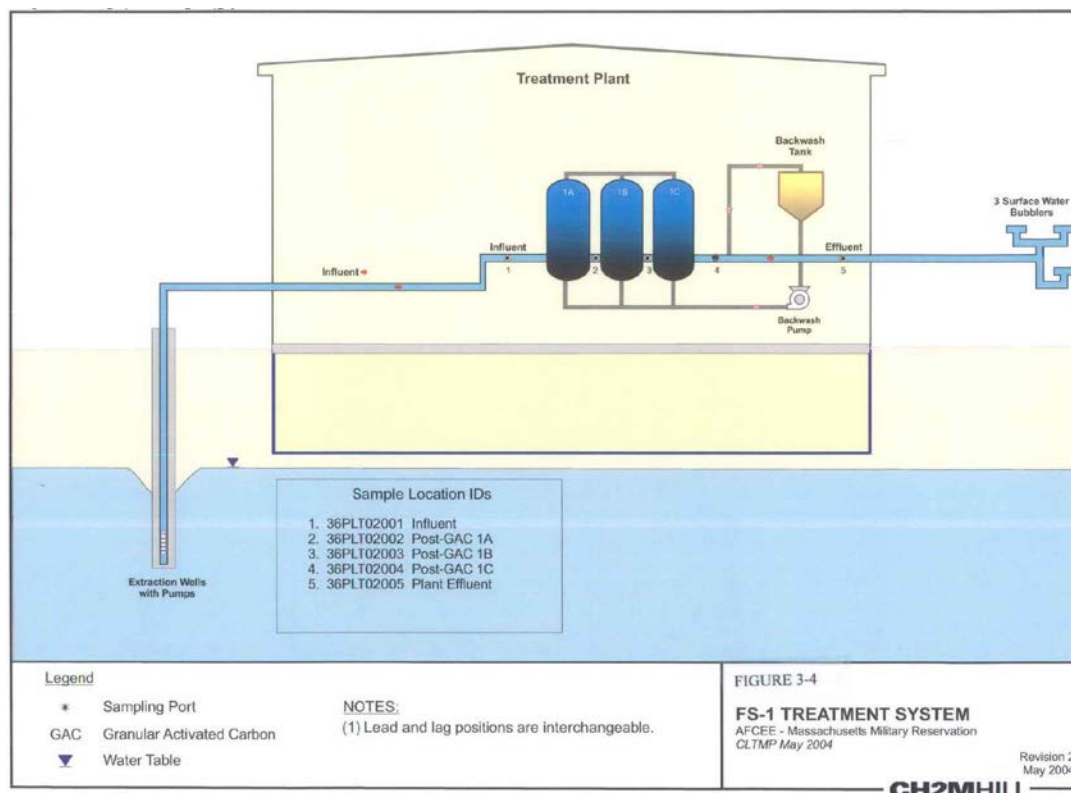
The FS-1 plume is now in long-term remediation, after AFCEE installed a second and final ETD system, which became operational in September of 2003. This system extracts and treats groundwater at a rate of 750 gpm using four extraction wells located in the south-central portion of the FS-1 plume in the Quashnet River cranberry bog area, just northeast of Johns Pond (see Appendix A, Map 2 for the location of FS-1 as of 2011). The southernmost extraction well replaced the previous 175 SWP system in November of 2003 (CH2M Hill 2012a). Three of the wells have screened intervals from -5 to -150 below msl and the fourth is screened 61 above to 51 below msl.

The system was designed to prevent upwelling of EDB contamination into the Quashnet River and associated cranberry bogs. The extracted groundwater is conveyed to a treatment plant with three 20,000-pound GAC vessels to remove EDB from the groundwater. The treated water is then discharged to the Quashnet River through a series of three vertical riser pipes, also known as oxygenating bubblers (CH2M Hill 2012a). These corrugated metal pipes are designed to cascade water out of the pipes in order to aerate and increase the dissolved oxygen content of the discharged water (AFCEE/MMR 2005).

In 2007, the ETD system was further optimized by turning off one of the four extraction wells and adjusting the flow of the other three, which resulted in a new extraction and treatment flow rate of 515 gpm. The well that was put offline is located in the FS-1 source area, and not in the FS-1 plume, and the 2000 FS-1 ROD stated no further action was needed in this area because EDB was not detected there (HWRAP 2000).

As of 2011, the system continues to operate at this same flow rate (CH2M Hill 2012a; AFCEE 2010). The diagram below (Figure 2-2) depicts the treatment process for FS-1 that has been in place since 2003.

Figure 2-2. Current FS-1 Treatment Process Flow Diagram



(Source: CH2M Hill 2004).

FS-12

In November 1997 the *Final Action Memorandum AOC FS-12 Source Removal* was finalized. This report outlined AFCEE's decision to conduct a time critical removal action at the FS-12 source. The selected removal action utilized an air sparging (AS)/ SVE system to remove petroleum hydrocarbons from the subsurface soil. This AS/SVE system operated between October 1995 and February 1998. Extracted contaminants were thermally destroyed by passing the soil vapor through a catalytic oxidation (cat-ox) unit. Since EDB is not readily removed by thermal oxidation, the gases were also run through a GAC unit. EPA and AFCEE later concluded in 1999 that the elevated EDB contamination would not be effectively addressed by the AS/SVE system (CH2M Hill, et al. 2008).

Meanwhile, in 1997, an extraction, treatment, and reinjection (ETR) system became operational, with a design flow rate of 772 gpm across 25 extraction wells. Treated groundwater was then returned to the aquifer through 22 injection wells. Groundwater was conveyed to the FS-12 treatment plant, where it was treated by a GAC system (CH2M Hill 2012b).

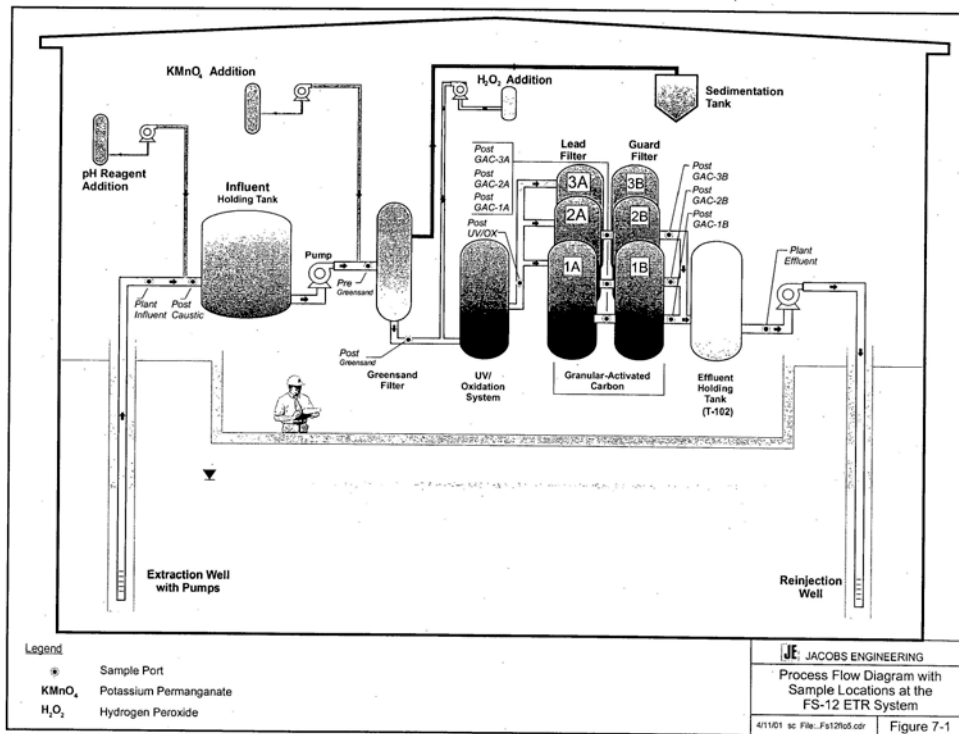
The GAC system at the FS-12 treatment plant originally utilized three vessel "trains," with two always in operation, and one on standby in case one of the other two needed to be taken off-line for a carbon media change-out. In 1999, the GAC system was reconfigured to optimize treatment of EDB by placing two of the trains in a parallel configuration, with inflow

groundwater directed equally to these two trains, and their effluent both directed to the third train. This configuration allows the two lead vessels to operate even after experiencing a contaminant breakthrough, as the third vessel continues to remove contaminants while the GAC media is replaced should one of the two lead vessels experience a breakthrough (AFCEE/MMR 2001). Frequency of GAC change-out is dependent on the concentration of organic compounds in the groundwater being treated; at FS-12, the GAC was replaced approximately once each four months. The spent GAC is transported offsite by the GAC supplier for recycling through a pyrolytic process that thermally removes and destroys the organic compounds (AFCEE/MMR 2001). The diagrams below depict the original FS-12 treatment process (Figure 2-3), and the reconfigured FS-12 GAC treatment process (Figure 2-4).

Just prior to the 2006 ROD, a 2005 feasibility study for FS-12 outlined three alternative treatment scenarios, which all were screened based on effectiveness, implementability, and cost. Alternative 1 called for no action as baseline conditions to which other alternatives would be compared. The no action alternative included stopping operation of existing EDR systems. Alternative 2 called for only long-term monitoring of the plume and tracking trends of contaminant concentrations and plume size. Alternative 3, the chosen alternative, maintained the monitoring and treatment system that was already in place. While this scenario had the highest cost, it was deemed to have the great effect on protecting human health (Jacobs 2005).

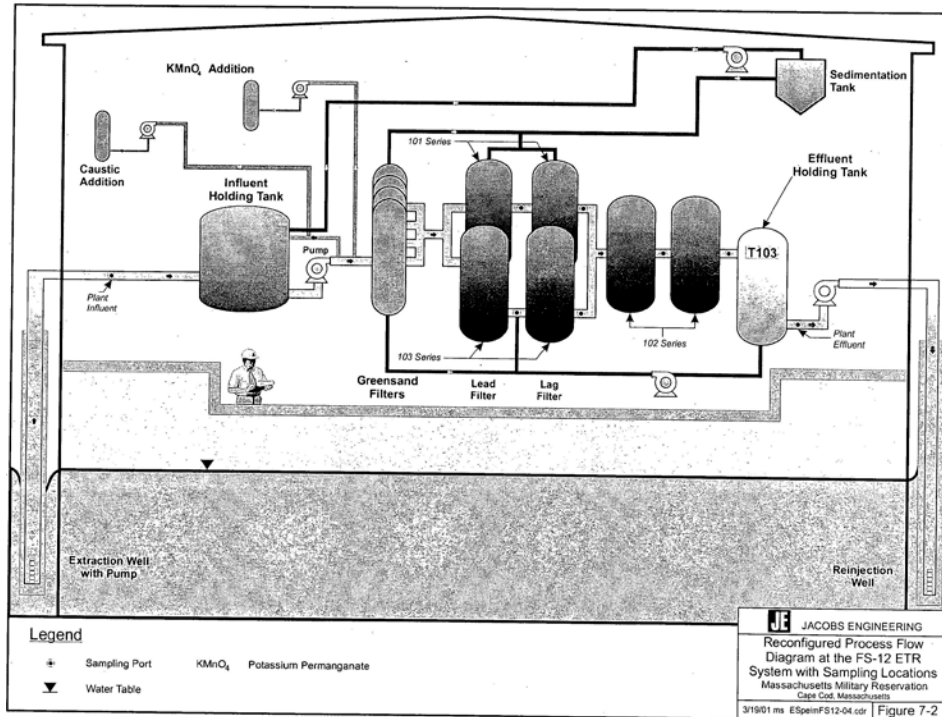
The FS-12 plume is currently in long-term remediation with a modified version of the same ETR system that was put online in 1997, as the 2006 ROD called for the status quo of operating and monitoring the existing system (AFCEE 2010). In 2011, the ETR system was modified again to use only four extraction wells at a flow rate of 360 gpm, and only 12 of the original 22 reinjection wells (see Appendix A, Map 3 for the location of FS-12 as of 2011) (CH2M Hill 2012b).

Figure 2-3. Original FS-12 Treatment Process Flow Diagram



(Source: AFCEE/MMR 2001).

Figure 2-4. Reconfigured FS-12 Treatment Process Flow Diagram



(Source: AFCEE/MMR 2001).

FS-28

In 1996, as a precaution, the Air Force installed a GAC system at the town of Falmouth's Coonamessett Water Supply Well (CWSW) to provide wellhead protection from the potential impacts of the FS-28 plume (Jacobs 2000a). In October of 1997 an ETD treatment system became operational for FS-28, which consisted of one extraction well (EW-1) located at the northern portion of the plume. This system was installed as part of a time-critical removal action to capture most of the plume mass at Hatchville Road and to minimize upwelling into the Coonamessett River system. Subsequently, in April 1999, AFCEE implemented a non-time-critical removal action which added additional extraction capacity to the system in the form of SWPs to eliminate the discharge of EDB to the Coonamessett River and neighboring cranberry bogs (Jacobs 2000a).

The extraction system's deep extraction well (EW-1) was screened from 160 to 220 feet bgs. The SWP uses a vacuum extraction system to extract water from up to 204 well-points. Each well-point is constructed of 2-inch diameter steel pipe installed to a depth of 13 feet bgs with a 2.3-foot or 3.0-foot screen. The well-points are connected using a polyvinyl chloride (PVC) header system. Water from the deep well and the shallow well-point extraction system are combined in the treatment plant. The treatment system is comprised of two 20,000-pound GAC vessels operating in series and has the capacity of treating 750 gpm. Treated effluent water is discharged to the Coonamessett River via two oxygenating bubblers (Jacobs 2000a).

A 2000 feasibility study for the FS-28 plume outlined seven remedial alternatives as follows:

1. No remedial action with long-term monitoring.
2. Continued operation of EW-1 and the CWSW wellhead protection system only.
3. Continued treatment system operations (EW-1, the CWSW wellhead protection system, and the shallow well-point extraction system).
4. Continued remedial operations with the addition of a new ETR system north of Coonamessett Pond to reduce aquifer restoration time and prevent plume migration under the pond.
5. Continued remedial operations with the addition of a new ETR system north of the western arm of Coonamessett Pond to reduce aquifer restoration time.
6. Continued remedial operations with the addition of a new ETR system in the area of Coonamessett Circle to reduce aquifer restoration time and prevent contaminants in the northwestern portion of the plume from migrating under the pond.
7. Continued remedial operations with the addition of a new ETD system in the Souza Conservation Area (immediately south of the western arm of Coonamessett Pond) to reduce aquifer restoration time.

The 2000 ROD for FS-28, which was a joint ROD with FS-29, selected Alternative 3 that essentially continued the status quo. This selected remedy was designed to take advantage of the naturally converging flow field surrounding the FS-28 plume to capture over 99 percent of the plume mass using the ETD systems AFCEE had already implemented as interim actions (Jacobs 2000a).

As of 2006, the deep extraction well was operating at a flow rate of 550 gpm and the SWP system at 200 gpm (CH2M Hill 2006). In 2007, the ETD system was expanded through the installation of a second well (EW-2) to remediate a deeper leading edge lobe of the identified to the south of both EW-1 and the SWP system. The screened interval for EW-1 is -149 to -169 below msl and for EW-2 is -132 to 148 feet below msl. The extracted water is also conveyed to the FS-28 GAC treatment plant and discharged to the Coonamessett River via two oxygenating bubblers (CH2M Hill 2012c).

A 2008 data gap investigation found that the SWP system had been successful in remediating the FS-28 plume in this area, but that it was no longer effective in remediating the residual EDB contamination near the SWPs. As a result, in 2010 the SWP system was permanently shut down. As of 2011, the FS-28 ETD system operated at a total flow rate of 625 gpm with 550 gpm extracted at EW-1 and 75 gpm at EW-2 (CH2M Hill 2012c).

FS-29

A 2000 feasibility study for the FS-29 plume outlined seven remedial alternatives as follows:

1. No remedial action with long-term monitoring.
2. Use institutional and engineering controls to prevent future residential exposure to FS-29 plume contaminants.
3. Construct a groundwater ETR system using GAC treatment to capture the plume.
4. Construct a groundwater ETR system using GAC treatment for mass removal within the plume.
5. Use recirculating wells to remove plume contaminants.
6. Use extraction wells with mobile GAC systems to capture the central portion of the plume.
7. Construct a groundwater ETR system to capture the central portion of the plume.

The 2000 ROD for FS-28 and -29 selected Alternative 3 for the FS-29 plume. The proposed actions were designed capture the FS-29 plume through axial extraction at the distal portion of the plume preventing any potential discharge to surface water bodies or human exposure to contaminated groundwater through private or municipal wells (Jacobs 2000a).

Unlike several of the other plumes at MMR, there was no existing treatment system in place at FS-29 prior to the ROD. As a result, the selected remedy for FS-29 includes the design, construction, and O&M of an extraction, treatment, and infiltration system to hydraulically capture and treat plume contaminants. Because available data on the FS-29 plume was limited at the time of the ROD, additional sampling and analysis was conducted over the next several years (Jacobs 2000a).

FS-29 is located in the area of three other contamination plumes (non-EDB), CS-4, 20, and 21, which together make up what are known as “the Southwest plumes.” Contaminated groundwater is captured by extraction wells in each plume, treated in a centrally located GAC treatment plant, and the treated water is returned to the aquifer through reinjection wells, an infiltration trench, and an infiltration gallery. The FS-29 treatment system, which was put online in 2006, includes

two extraction wells working together at a rate of 525 gpm. Extracted water is sent to the GAC treatment plant, and treated water is discharged via an infiltration trench (CH2M Hill et al. 2008).

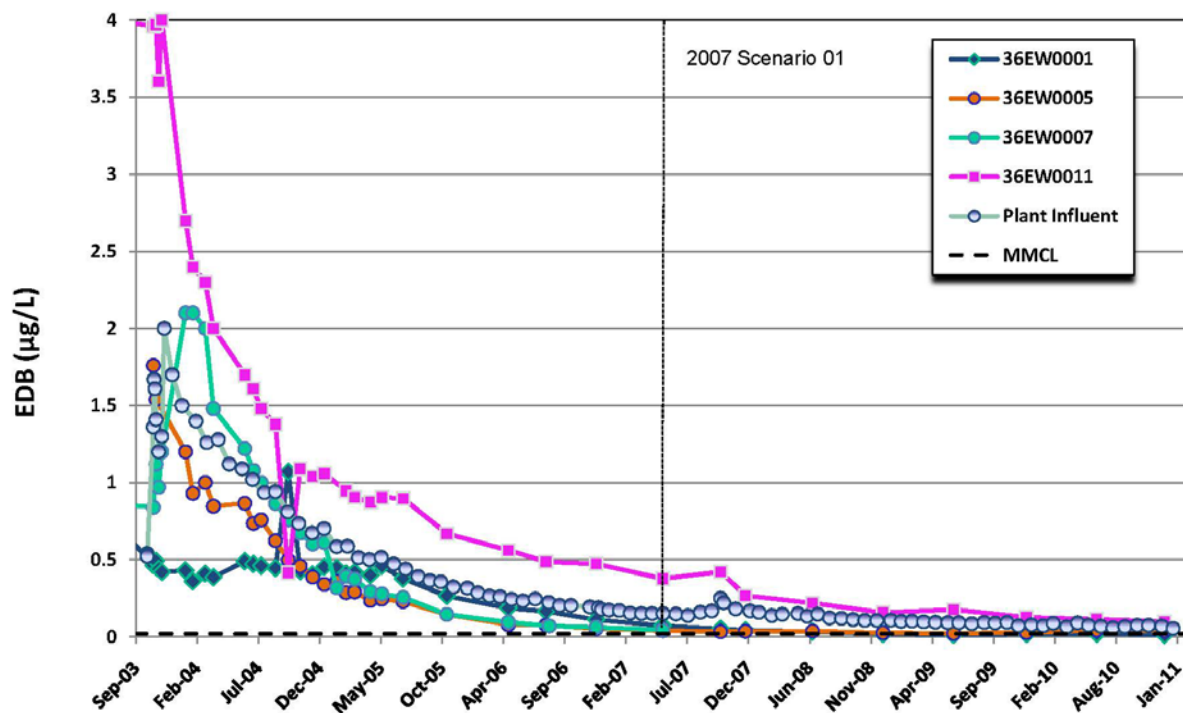
The selected alternative presented in the 2000 ROD anticipated that all of the groundwater within the FS-29 plume would be captured by the remedial system; however, the final design allowed the groundwater contamination in the downgradient leading edge of FS-29 to reach cleanup levels through natural attenuation instead of through active remediation. As a result, in March of 2008 the system was optimized by reducing the flow rate from the two extraction wells to a total of 373 gpm (CH2M Hill et al., 2008).

2.3.1 EFFECTIVENESS OF REMEDIATION TECHNOLOGIES

FS-1

The latest test results showed that the FS-1 treatment system has been successful in reducing both the amount of EDB in the FS-1 plume and the EDB concentrations in the surface water of the Quashnet River and associated bogs (AFCEE 2010). Since cleanup began in 1999 through the beginning of 2012, a calculated estimate of 17.87 pounds of EDB have been removed, and 3.8 billion gallons of groundwater have been treated, an amount that could fill the volume of 14 Empire State Buildings. The graph below (Figure 2-5), shows the influent concentration of EDB in each of the four extraction wells at FS-1 from September 2003 through January 2011, which have gotten progressively smaller, and are approaching the MMCL of 0.02 $\mu\text{g/L}$ (CH2M Hill 2012a).

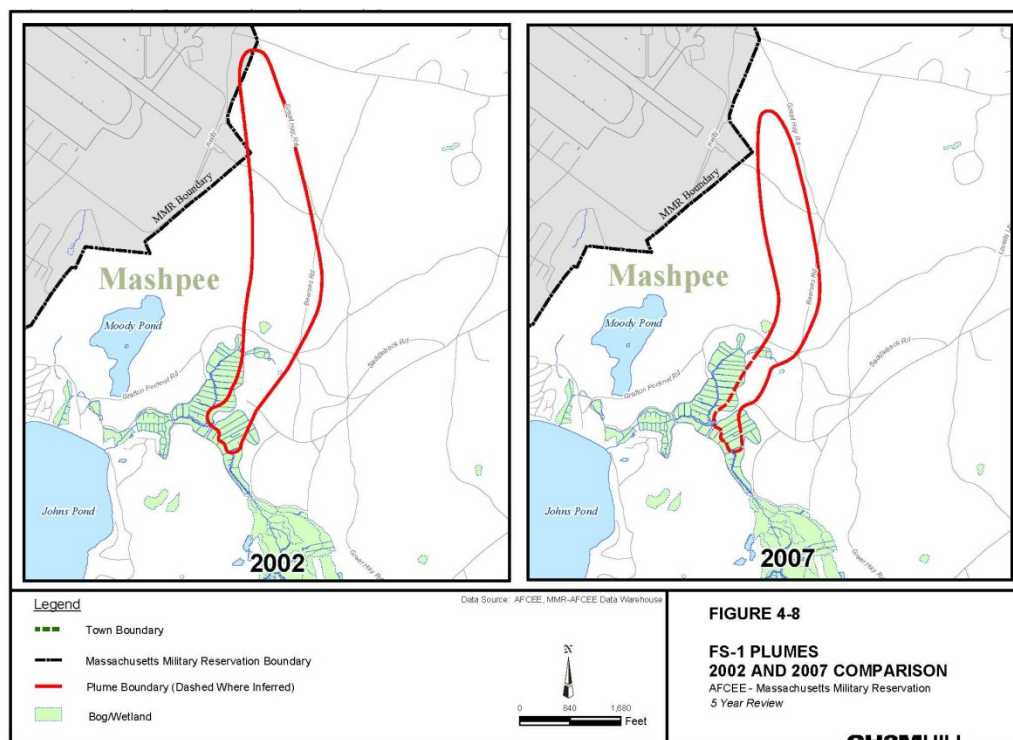
Figure 2-5. FS-1 Extraction Well and Plant Influent Data (2003 – 2011)



(Source: CH2M Hill 2012a).

In addition to progress in reducing influent EDB concentrations in FS-1, the boundary of plume has shrunk significantly since remediation activities began. Figure 2-6 depicts the extent of the FS-1 plume in 2002, and again in 2007.

Figure 2-6: FS-1 Plume Boundary in 2002 and 2007



(Source: CH2M Hill et al., 2008).

FS-12

The latest test results indicate that the extraction wells continue to successfully contain the FS-12 groundwater plume (AFCEE 2010). Since cleanup began in 1997 through the beginning of 2012, a calculated estimate of 135.7 pounds of EDB have been removed, and 4.4 billion gallons of groundwater have been treated, an amount that could fill the volume of almost 16 Empire State Buildings (CH2M Hill 2012b). Concentrations of EDB in the groundwater reached a high of 890 $\mu\text{g/L}$ in 1996, but have since been reduced to 21.4 $\mu\text{g/L}$ in 2011. Most groundwater samples in 2011 were seeing EDB concentrations at less than 1 $\mu\text{g/L}$ (AFCEE 2010; CH2M Hill 2012b).

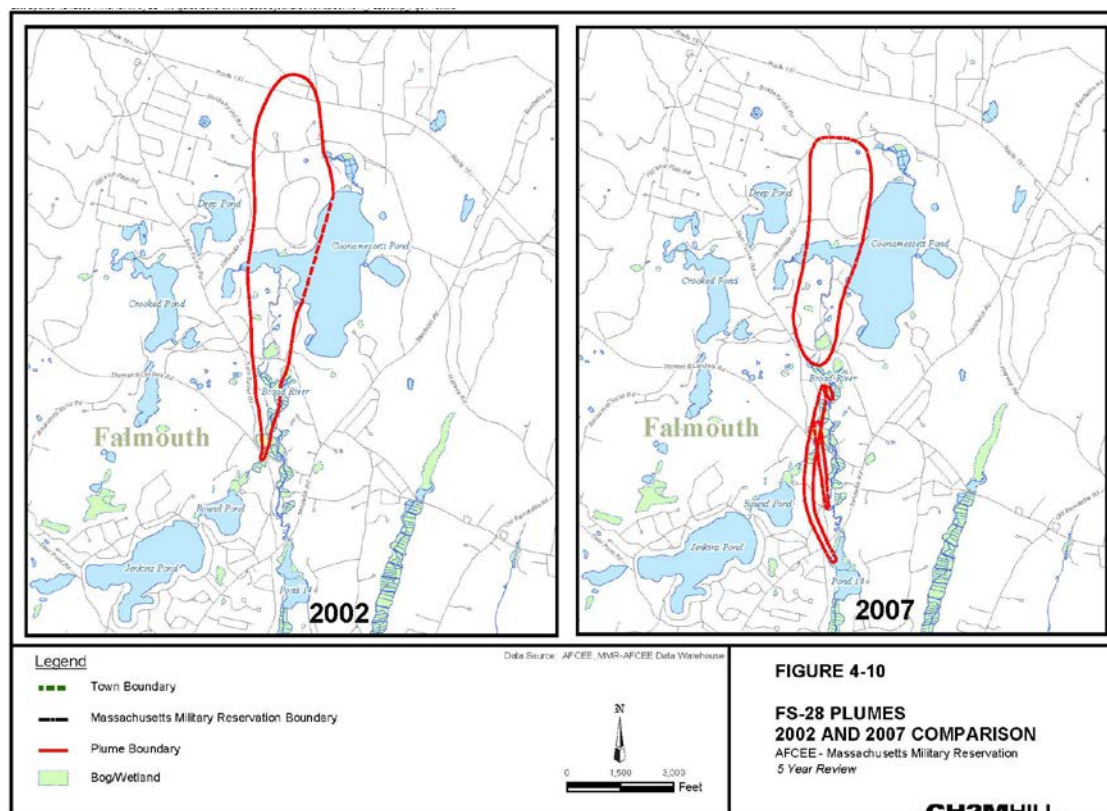
The areal extent of the plume remained rather stable from 2002 to 2011 as shown in Figure 2-7 and in the attached Appendix A, Map 3. Figure 2-8 below shows that the areal extent decreased significantly from 1996 to 2004.

FS-28

Ongoing groundwater sampling shows that the remediation processes in place at FS-28 have been successful at both lowering the EDB contamination levels of the plume, and shrinking the overall plume size. In 1997 the maximum level of EDB was measured at 18 $\mu\text{g/L}$, but most recent sampling results show a maximum level of EDB of 1.1. In addition, out of 68 groundwater samples from FS-28 in 2011, 31 showed no EDB above the detection limit, and nine were at or below the MMCL (CH2M Hill 2012c).

In 2000, FS-28 was one large plume with an estimated 4.4 billion gallons of contaminated groundwater, as depicted in Appendix A, Map 4 (Jacobs 2006a). By 2006 the plume had shrunk to an estimated 1.8 billion gallons of contaminated groundwater. Figure 2-9 shows FS-28 in 2002 and again in 2007 when it is no longer one large continuous plume, but is broken up into four smaller pieces (see Appendix A, Map 6 for the plume as of 2011) (CH2M Hill et al., 2008). Since remediation began in 1997, the ETD system has removed an estimated 14.68 pounds of EDB through treatment of 4.9 billion gallons of water (CH2M Hill 2012c).

Figure 2-9. FS-28 Plume Boundary in 2002 and 2007



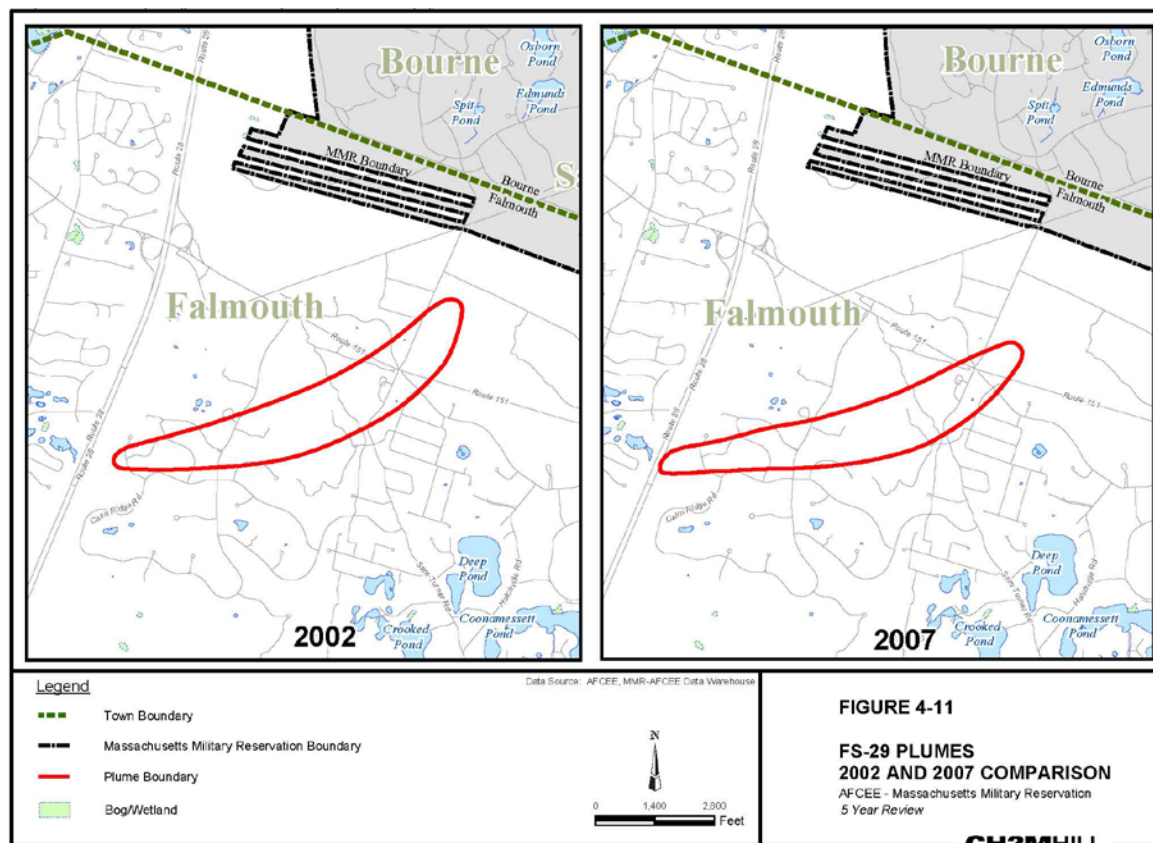
(Source: CH2M Hill et al., 2008).

FS-29

Of the four EDB plumes at MMR, FS-29 has shown the least progress, but this is mostly due to the fact that the remediation has been ongoing for a much shorter period of time. In addition, the maximum EDB concentrations of FS-29 have always been considerably lower than the other three plumes. Nevertheless, the FS-29 treatment system has been effective in reducing the level of EDB since remediation began in 2006. In 2001, which was the historic maximum of EDB contamination at FS-29, EDB was found at up to 0.318 $\mu\text{g/L}$. By 2009, after three years of treatment, the maximum EDB concentration was 0.081 $\mu\text{g/L}$ (AFCEE 2010). From start of remediation in September 2006 through the end of 2007, the FS-29 remediation system had treated 347 million gallons of groundwater and removed an estimated five pounds of EDB (CH2M Hill 2012c).

Figure 2-10 depicts EDB concentrations at FS-29 in 2002 and again in 2007. As the treatment system had only been operational for one year in 2007, little difference between the 2002 and 2007 maps is noted.

Figure 2-10. FS-29 Plume Boundary in 2002 and 2007



(Source: CH2M Hill et al., 2008)

2.3.2 COSTS OF REMEDIATION TECHNOLOGIES

FS-1

The remediation activities were expected to take seven years and cost approximately \$12 million (\$6.4 million for capital costs, \$4.2 million for O&M, and \$1.6 million for the pilot test system) (HWRAP 2000). A 2005 remedial action report on FS-1, however, found that after six years of cleanup activities (plus an estimate for the seventh year), costs had actually been \$18.2 million. This is almost a 50% increase over the original estimate. The 2005 report also estimated that the project would be completed in 2033, and would cost an additional \$16.8 million in ongoing O&M, for a total project cost of \$35 million (AFCEE/MMR 2005). Since a 2012 update report projected the FS-1 cleanup end date to be 2020, it is possible that total costs might not actually reach \$35 million, although the initial estimates did prove to be underestimate costs (CH2M Hill 2012a).

In December of 2009, AFCEE put a new 1.5 megawatt wind turbine in operation, which is expected to reduce electricity costs and carbon emissions by 25% to 50% (AFCEE 2010). Electricity consumption costs, however, amount to only a small portion of the total remediation cost, so the wind turbine is not likely reduce the final project cost by a significant amount (AFCEE/MMR 2001).

FS-12

As of the end of FY 2000, AFCEE had spent \$24.3 million on construction of the FS-12 ETR system, \$9.4 million on other costs, including \$3.3 million for O&M from 1997 through 2000. Electricity has not been a significant cost, totaling only \$450,000 since the system was put online in 1997 through 2000 (AFCEE/MMR 2001).

As with FS-1, the most involved and thorough alternative was chosen in the FS-12 2006 ROD, out of choice of three alternative treatment scenarios. The ROD estimated that O&M and monitoring of the treatment of the FS-12 plume would cost \$22.4 million from 2006 to the expected completion date of 2035 (Jacobs 2006). Actual costs beyond 2000 were not found for FS-12. Since current estimates of the remediation end date are now 2048, the 2006 ROD fails to capture approximately 13 year of O&M costs, which will likely drive the cost of remediation higher. However, the estimate for the duration until remediation is complete is uncertain, the actual O&M costs may be different from those estimated in the ROD, and remediation system optimization may improve efficiencies, which taken together make the projected total costs speculative.

FS-28

According to the 2000 ROD for FS-28, the remediation was expected to last 18 years, and cost a total of \$7.1 million, which includes annual O&M cost of \$680,000. This figure did not include the costs for the construction of treatment systems already in place prior to the ROD, which includes the EW-1 extraction well (\$670,000), the CWSW wellhead treatment system (\$470,000), and the SWP system (\$2.65 million) (Jacobs 2000a; Jacobs 2000b). Since groundwater transport modeling done in 2004 found that remediation is expected to last through 2047, the actual costs will likely be significantly higher (CH2M Hill 2012c). No actual costs

were found for FS-28. As indicated above for FS-12, the estimate for the duration until remediation is complete is uncertain, the actual O&M costs may be different from those estimated in the ROD, and remediation system optimization may improve efficiencies, which taken together make the projected total costs speculative.

FS-29

At the time of the 2000 ROD, it was estimated that total cost of remediation for FS-29 would be \$11 million. This included \$6.6 million for the construction of the remediation system and \$740,000/year for 11 years of O&M (Jacobs 2000a). Since most recent estimates from 2010 show that remediation of FS-29 should be complete in 2018, it is possible that actual costs will come close to estimates, though no actual costs were found for FS-29 (AFCEE 2010).

2.3.3 CLEANUP STATUS/RESULTS

FS-1

The remediation of FS-1 is ongoing, but has shown significant progress since it began in 1999, as noted above. While the original ROD for FS-1 expected remediation to take seven years, a 2005 remedial action report projected cleanup would reach the goal of lowering EDB concentrations below the MMCL in 2033, but then most recent estimates from 2012 project that the cleanup project will be completed in 2020. In 2012, one of the four extraction wells was pulling up water at levels below the EDB MMCL, so it possible that this extraction well will be taken offline in the near future (AFCEE/MMR 2005; CH2M Hill 2012a). See Section 2.3.1 for more details on the results the remediation of FS-1.

FS-12

The remediation of FS-12 is ongoing, but has shown significant progress since it began in 1997, as noted above. While the original ROD for FS-12 expected remediation to last through 2035, the cleanup project is expected to be completed in 2048 (Jacobs 2006; AFCEE 2010). See Section 2.3.1 for more details on the results the remediation of FS-12.

FS-28

The remediation of FS-28 is ongoing, but has shown significant progress since it began in 1997, as noted above. However, while the original ROD for FS-28 expected remediation to last through 2018, the cleanup project is now expected to be completed in 2047 (Jacobs 2000a; AFCEE 2010). See Section 2.3.1 for more details on the results the remediation of FS-28.

FS-29

The remediation of FS-29 is ongoing, but has already shown some progress since it began in 2006, as noted above. At the time of the 2000 ROD, remediation was expected to last 11 years. Because remediation didn't begin until 2006, the original estimate of the date of completion would have been 2017 (Jacobs 2000a). As of 2010, the expected project finish date is 2018 (AFCEE 2010). Of the four EDB plumes at MMR, FS-29 is currently the only one that is expected to complete its remediation anywhere near the ROD's original estimates. See Section 2.3.1 for more details on the results the remediation of FS-29.

2.3.4 PROBLEMS ENCOUNTERED

Remediation of the four EDB plumes at MMR has generally continued as planned in each original ROD. Although each plume experienced optimizations to their treatment systems over the years, optimizations were done largely for the sake of efficiency and not as a result of problems being encountered. There were, however, a few setbacks for the FS-1 treatment system. As mentioned above, the pilot system at FS-1 operated until 2002 when a fire destroyed the treatment plant. The cause of the fire was not stated in collected documents. As a result of the fire, extraction and treatment was discontinued for a year while a new treatment plant was constructed (CH2M Hill 2012a). In addition, the former shallow groundwater infiltration trench, installed for the pilot test system, is no longer utilized at FS-1. During the pilot test operation, the infiltration ditch experienced flooding (discharging water to the surface), and it was found that bypassing the infiltration ditch and discharging the flow through bubblers resulted in improved stream conditions more favorable for fishery habitat, including trout spawning (AFCEE/MMR 2005).

The most significant issues at MMR are related to the fact that the entire remediation process has been subject to a large amount of community concerns and negative press coverage. Back in 1978, when contaminated groundwater was first detected, there was “virtually no opportunities for the public to be informed and involved in the process.” The only advisory committee at the time was closed to the media and general public (AFCEC 2013). In addition to concerns about contaminated drinking water for themselves, residents feared that they would lose their tourist industry without a reliable clean source of water (Brennan 2011).

A full 13 years later in 1991, the first community involvement plan was implemented, which laid the groundwork for improving the relationship between the military and the community. The plan created the first ever citizen advisory team in 1991, which was made up entirely by local citizen volunteers (AFCEC 2013). While there is still some disagreement about the level of remediation needed between EPA regulators and the Air Force, which is funding the cleanup, there is “a growing respect on both sides has avoided some of the public battles that erupted in the early days when meetings could easily devolve into yelling and finger-pointing” (Brennan 2011).

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3.0 HOME OIL

3.1 HOME OIL BACKGROUND

Home Oil Company Bulk Plant is located on the north side of U.S. Highway 83 in the town of Selden in Sheridan County, Kansas. Sheridan County is in the northwestern part of the state. Selden has a population of approximately 200 and a land area of 0.3 square miles. The town is surrounded by agricultural land, and there are no surface water bodies or sensitive environments located within close proximity. Groundwater in the area flows generally to the east-southeast, but can be influenced locally by extraction of a high volume of groundwater from wells. The nearest towns are Oberlin, approximately 20 miles north and Colby approximately 30 miles southwest (PLERI 1991).

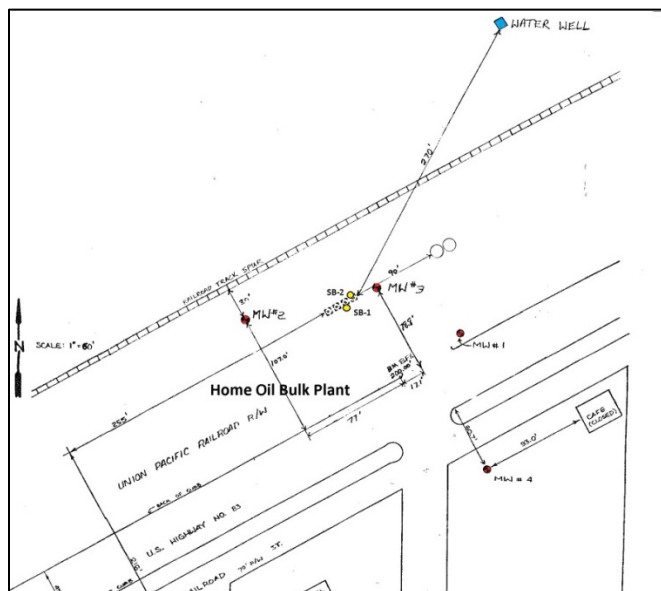
The Home Oil Bulk Plant is located north of the town across Highway 83 on Union Pacific right-of-way. Rail America tracks run north of the site, beyond that is farmland and pasture. Large co-op fertilizer tanks are located east of the site, and Rail America property continues to the west. From 1978 until 1989, Home Oil Company, Inc. Selden leased the property from the previous owner, Kyle Railroad (EGEI 1996). At that time, there were four existing underground storage tanks (USTs) onsite that stored petroleum products: one 17,000-gallon tank and three 12,000-gallon tanks that were assumed to be installed in the early 1930s. These tanks were used by Home Oil from 1978 until 1985 and removed in 1989 when contamination was first discovered. During removal of the four tanks, the 17,000-gallon tank was found to have numerous holes from corrosion and soil samples taken during the tank excavations found soil concentrations of total petroleum hydrocarbons (TPH) above the Kansas Department of Health and Environment (KDHE) MCLs for TPH to a depth of 30 feet bgs. As a result of the initial findings, Home Oil was accepted into the KDHE Trust Fund Program in 1990 (PLERI 1991).

In 1991, an initial SI was conducted to determine the horizontal and vertical extent of the contamination from the leaking USTs. Two soil borings and four monitoring wells were installed to delineate the extent and determine subsurface saturated and unsaturated hydraulic conductivity (Figure 3-1).

Soil boring 1 (SB-1) was drilled to a depth of 55 feet bgs where the leaking 17,000-gallon tank had been removed. Soil boring 2 (SB-2) was drilled 20 feet east of SB-1 to a depth of 35 feet bgs. All four monitoring wells were drilled to 140 foot bgs depths.

Analytical results from soil sampling in the vicinity of the tank removal reported TPH and benzene above the KDHE MCLs. TPH was detected in soil at greater than 2,500 milligrams per kilogram (mg/kg) to depths of 20 to 41 feet, and benzene at 350 micrograms per kilogram (µg/kg) to 20-25 feet bgs. Groundwater analytical results for MW-1 were above the KDHE MCLs for xylene, toluene, and benzene. No free phase product was encountered (PLERI 1991). Analysis for EDB was not included until 1995.

Figure 3-1. Initial Soil Borings and Monitoring Wells



(Source: PLERI 1991)

The town of Selden operated two municipal wells in the vicinity of the Home Oil site. Public water supply well (PSW)-2 approximately 270 feet northeast of the property, and PSW-3 approximately 0.37 miles east-southeast at the edge of town. During routine testing in 1995, EDB was discovered in PSW-3 above the KDHE MCL of 0.05 $\mu\text{g/L}$ (KDHE 2011). Pump tests run on PSW-2, the town's back up well, showed no initial communication with the plume. PSW-3 is located directly downgradient from the Home Oil site while PSW-2, located northeast of the site, was not affected. After confirmation sampling, the town of Selden notified residents of the contamination and provided bottled water through the local grocery store. The contaminated well, PSW-3, was shut down and PSW-2 was used for 90 days as the primary water supply. By August 1995, a new municipal well (PSW-4) was installed one mile north of the site up gradient from the contamination (EGEI 1997). One domestic farm well down gradient of PSW-3 was eventually found to be contaminated with EDB and a GAC treatment system was installed on the well as wellhead protection. High-volume irrigation wells in the surrounding area were thought to contribute to the spread of the contamination by lowering the local water table elevation and changing the groundwater flow direction and rate (McGuire and Wilson 2010).

In 2009, the site was considered for closure, but additional wells in the area that were not part of the Home Oil Company site remediation were found to have significant levels of EDB and 1,2-DCA. All of the wells sampled were outside the influence of Home Oil remedial system. A separate remedial system will be installed to address the source of the additional contamination. KDHE was able to remediate the outlying plume quickly without installing an AS/SVE system by utilizing knowledge gained during implementation and operation of the Home Oil remedial system. According to Emily McGuire, Professional Geologist (P.G.) with the Kansas Storage Tank Section, the remedial system remains in operation today for low levels of 1,2-DCA; EDB is no longer a contaminant of concern at the site.

Soils at the site consist of various silts, fine sands, and weakly cemented sandstone layers to a depth of 140 feet bgs. The Ogallala Aquifer is the principal beneficial use aquifer beneath the site and the primary water source for the town of Selden and the surrounding area (EGEI 1996). Shallow groundwater occurs in alluvial sediments at a depth of 125 to 130 feet bgs. Prairie Dog Creek is four miles north of the site and the north fork of the Solomon River is five miles south. Both are intermittent streams and are not thought to significantly impact groundwater in the area (PLERI 1991; EGEI 1997).

Contaminated groundwater from the Home Oil Bulk Plant release is moving southeast at a rate of 0.33 feet per year based on the hydraulic conductivity of 5.0×10^{-7} centimeters per second (cm/sec) in the saturated zone. An estimated hydraulic conductivity of 1.18×10^{-2} cm/sec in the unsaturated zone indicates that the soil is fairly impermeable (PLERI 1991).

3.2 EDB CONCENTRATIONS IN CONTAMINATED MEDIA

EDB characterization at the site began in 1995 with the activities and sampling results from the remedial design phase of the investigation and continues today. Analytical results from groundwater monitoring wells, SVE extraction wells, AS injection wells, and soil vapor observation wells were used to delineate and track concentrations of EDB and other hydrocarbons at the Home Oil Site. Sampling for EDB began in 1995 and continues today. The 2013 Quarterly Monitoring Report for the site reports the highest concentrations of EDB detected in site monitoring wells and the drop in EDB concentration after remediation (Table 3-1) (MESI 2013).

Table 3-1. Concentrations of EDB in Site Monitoring Wells from 1995 to 2013

Monitoring Well ID	Highest EDB Concentration (µg/L)	Year	Last EDB Concentration (µg/L)	Year
MW-1	96.2	1996	<0.030	2009
MW-2	<50	1995	<1.0	2007
MW-3	115	1996	<0.028	2010
MW-8	6.2	1996	<1.0	2007
MW-11	15.1	1996	<0.028	2010
MW-14*	29.6	1995	<0.030	2012
MW-23	16.9	2000	<0.028	2010
MW-24	19.7	2000	<0.030	2013
MW-25	9.1	2003	<0.030	2011
MW-26	55.2	2001	<0.029	2013
OBW-1	82.6	2000	<0.029	2010
OBW-2	48	2002	<0.028	2010
OBW-3	8.5	2001	<1.0	2007
PW-1	57	1995	<0.030	2010

*MW-14 was installed as part of the Home Oil Station site investigation. (source: MESI 2013)

EDB- ethylene dibromide < - less than

µg/L – micrograms per liter

A percentage of samples were split and sent to EPA for EDB analysis. Samples results shown as not detected (ND) are below the method detection limit of 0.0013 µg/L. Results from the split samples for June and September of 2009 are shown in Table 3-2.

Table 3-2. EPA Split Sample Results for EDB June and September 2009

Field Sample ID	Collected	Result (µg/L)	Collected	Result (µg/L)
MW-3	6/26/09	ND	9/28/09	ND
MW-11	6/26/09	ND	9/28/09	ND
MW-23	6/26/09	ND	9/28/09	ND
MW-24	6/26/09	0.12	9/28/09	ND
MW-26	6/26/09	0.64	9/28/09	ND
OBW-1	6/26/09	ND	9/28/09	ND
OBW-2	6/26/09	ND	9/28/09	ND

(source: SEII 2009)

ND = Not Detected (or non-detect)

µg/L – micrograms per liter

Kansas State Water Plan Monitoring wells were sampled from 2012 to 2013. Results for wells in the vicinity of the plume are shown in Table 3-3. Well locations are shown on Attachment 1.

Table 3-3. Concentrations of EDB in KDHE Water Plan Monitoring Wells, 2010-2013

Monitoring Well ID	Highest EDB Concentration (µg/L)	Year	Last EDB Concentration (µg/L)	Year
MW-A1	0.066	2010	<0.029	2013
MW-A2*	0.130	2011	0.110	2012
MW-A3*	0.088	Mar 2010	<0.029	Jun 2010
MW-B1	<0.028	Sep 2010	<0.029	Dec 2010
MW-B2	0.076	2010	<0.030	2013
MW-B3	0.38	2000	<0.029	2012

*Wells were destroyed, no additional data available. (source: MESI 2013)

< - less than

µg/L – micrograms per liter

3.3 REMEDIATION TECHNOLOGIES USED

In 1991, four monitoring wells were installed to a depth of 140 feet bgs and two soil boring were taken in the vicinity of a UST removal at the Home Oil Bulk Plant. From 1995 to 1997, activities were conducted as part of the Remedial Design Plan approved by KDHE to obtain the field data required to further delineate and track the contamination and develop a remediation plan.

- Twelve shallow monitoring wells (MW-5 through MW-12; MW-23 through MW-26), one intermediate well (MW-13M), and one deep monitoring well (MW-13D) were installed to delineate the contamination boundaries.
- One pump test well (PW-1) and one observation well (OB-1) were installed to perform aquifer pumping tests.
- One shallow soil vapor extraction (SVE) well (SVE-1), three shallow soil vapor observation wells (VOBW-1 through VOBW-3), two deep SVE wells (SVE-2, DSVE-4), and three deep soil vapor observation wells (VOBW-4 through VOBW-6) were installed to perform soil vapor extraction tests on the shallow and deep formations.
- Two air sparge wells (AS-1, AS-2) were installed along with two air sparge observation wells (OBW-2, OBW-3) to perform multiple air sparge pilot studies.

Three 8-hour SVE tests, three 8-hour AS tests, and two 24-hour pump tests were completed after installation of the wells. Sixty eight groundwater and 30 soil samples were collected and submitted for laboratory analysis (EGEI 1997). Analytical results from the remedial design test samples confirmed BTEX, EDB, and 1,2-DCA as constituents of the Home Oil Company Bulk Plant groundwater plume (EGEI 1997). Free-phase product (i.e., LNAPL) was discovered in a well during well installation (EGEI 1997), but LNAPL was detected during sampling events (EGEI 1996). Well drilling logs identifying the components of the subsurface stratigraphy indicated the soil conditions at the site were conducive to SVE/AS systems, and that system would influence the bulk of the contaminant plume. The tests also indicated that the components of the plume were highly volatile and easily removed by a SVE/AS system. The SVE system would remove vapors released during air sparging and reduce the risk of vapor migration (EGEI 1997).

Three alternatives for hydrocarbon remediation were considered for the Home Oil site: passive remediation, groundwater recovery and treatment and a combination of soil venting and air sparging. Passive remediation, such as monitored natural attenuation (MNA), was ruled out due to high contamination levels, costs associated with obtaining and evaluating the biological data necessary to develop a remediation plan, and the close proximity of the plume to drinking water sources. Groundwater extraction and treatment (ETD or ETR) was not considered due to water conservation considerations and high installation and operating costs. Air sparging was selected to remediate groundwater in combination with a SVE system to control vapor migration. Prior experience with the combination of systems and preliminary testing indicated that conditions at the site, such as the volatility of the compounds, large grain and pore size in site soils, and depth to groundwater, would greatly increase effectiveness. Air sparging and SVE are relatively inexpensive to install and operate, aggressively remediate the source, and shorten remediation time (EGEI 1997).

During the remedial design phase, an SI at the Home Oil Station, located southwest of the Home Oil Bulk Plant across Highway 83, discovered a release of petroleum products. The Home Oil Station release was thought to be the result of overfilling and after evaluation was ruled out as a possible source for the contamination at the Home Oil Bulk Plant (EGEI 1996; McGuire and Wilson 2010).

Phase I of remediation at the Home Oil site began in 1999 with the installation of 12 SVE wells screened at various intervals (three shallow, six intermediate, and three deep). Six air sparge injection wells were installed with screened intervals 28.5 feet below the static water level (SWL) in anticipation of a steady decline in the Ogallala water levels. Previously installed monitoring wells MW-1 through -12 and MW-23 through -26 were sampled for groundwater analysis during remediation. After implementation, the free phase product plume decreased in area and thickness and EDB levels decreased over 90 percent (McGuire and Wilson 2010).

To remediate the remaining contamination, a reevaluation/retooling of the remediation system was conducted in 2007. As a result, five new shallower AS injection wells were installed to replace existing injection wells. The wells were screened at 12 feet instead of the original 28.5 feet below SWL because Ogallala water levels had not dropped as anticipated. Several additional SVE wells were also installed, and when possible the new wells were tied to existing piping (McGuire and Wilson 2010). Wells have been sampled quarterly from 1999 till the present (MESI 2013). Table 3-4 shows the total wells installed from 1991 to 2007. A diagram of AS/SVE well detail is shown below in Figure 3-2; Figure 3-3 shows the layout of the AS/SVE remediation system wells and the piping plan for the remediation system is shown in Figure 3-4. Figures 3-5 and 3-6 illustrate the zones of influence for shallow and deep SVE wells in the remedial system.

Although the plume extends beyond the remedial system zone of influence, oxygenated water from the system travels approximately 500 feet per year remediating groundwater downgradient from the system (note however, that biodegradation rates for EDB are much slower under aerobic conditions than under anaerobic conditions for reductive dehalogenation) (McGuire and Wilson 2010).

3.3.1 EFFECTIVENESS OF REMEDIATION TECHNOLOGIES

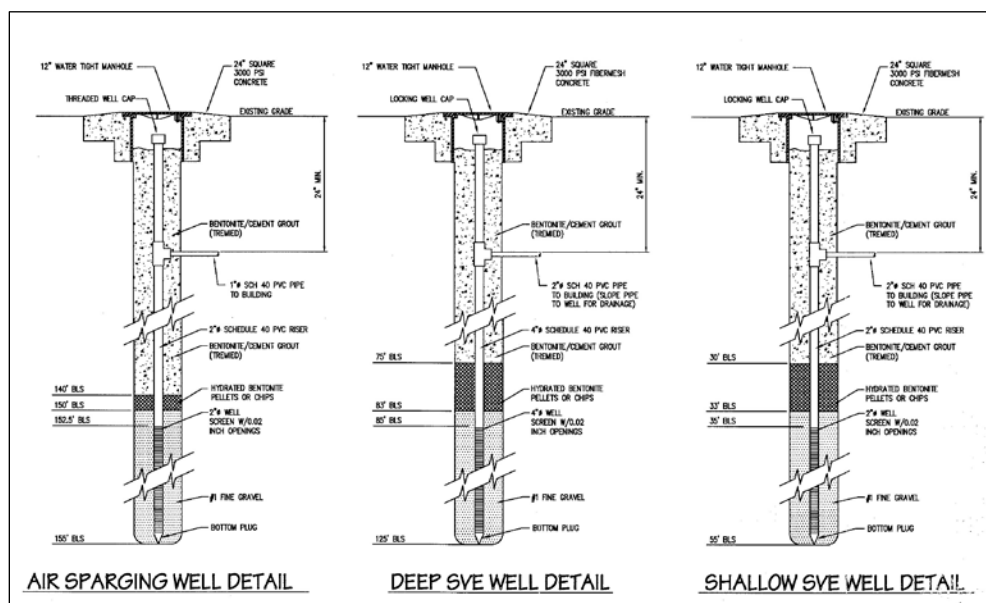
From 1996 to 2010, the Home Oil EDB plume decreased in size and concentrations fell below the KDHE MCL for EDB of $0.05 \mu\text{g/L}$. Oxygen enriched water from the source area travels at approximately 500 feet per year and will continue to clean up residual BTEX contamination outside the influence of the remediation system and EDB contamination at a slower rate (McGuire and Wilson 2010). Figure 3-7 shows the original extent and concentrations of EDB in the Home Oil Company Bulk Plant plume and the decrease in size and concentration by 2010.

Table 3-4. Types of Monitoring and AS/SVE Wells Installed for the Home Oil Company Bulk Plant Remediation

Well Type	Total	Screened Interval (feet bgs)	Year of Installation
Monitoring	18	110-140 (16 shallow) 169-179 (1 intermediate) 196-206 (1 deep)	4 in 1991 and 14 in 1997
Pump Test	1		1997
AS Observation	2		1997
AS	12	139-142 152-155	2 in 1997, 6 in 1999, and 4 in 2007
SVE Observation	6	35-55 (3 shallow) 105-125 (3 deep)	1997
SVE	14	35-55 (shallow) 85-125 105-125	2 in 1997, 12 in 1999, and 4 in 2006-07

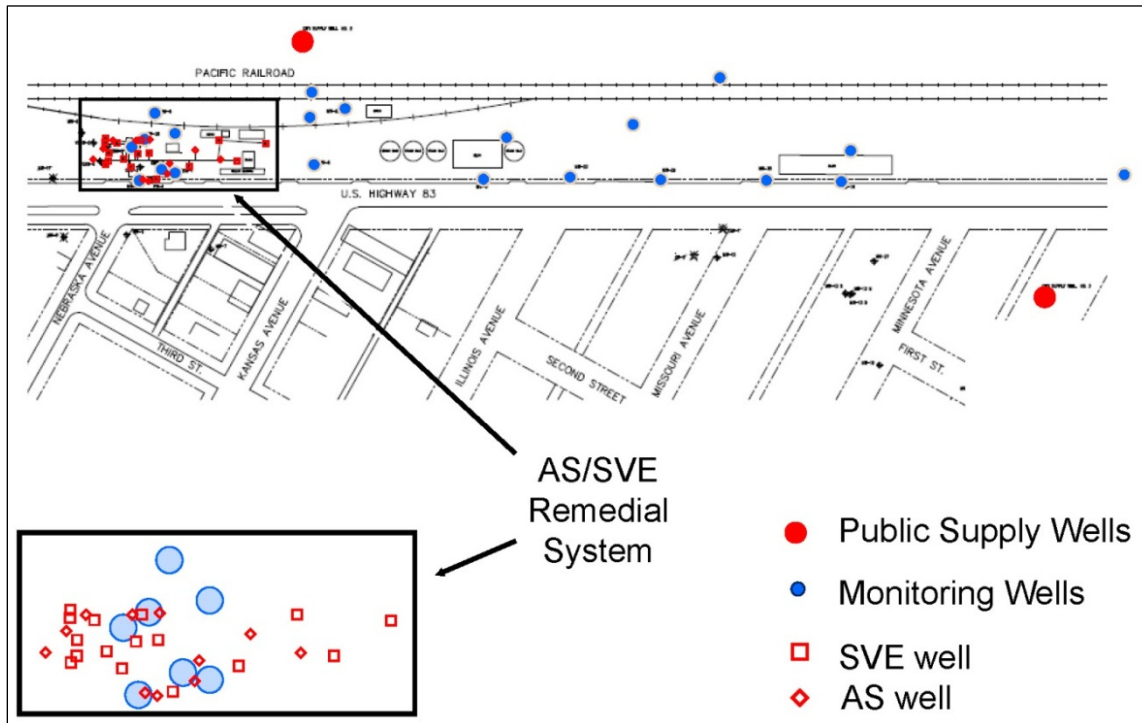
AS – air sparge
bgs – below ground surface
SVE – soil vapor extraction

Figure 3-2. Diagram of AS/SVE Remediation Wells



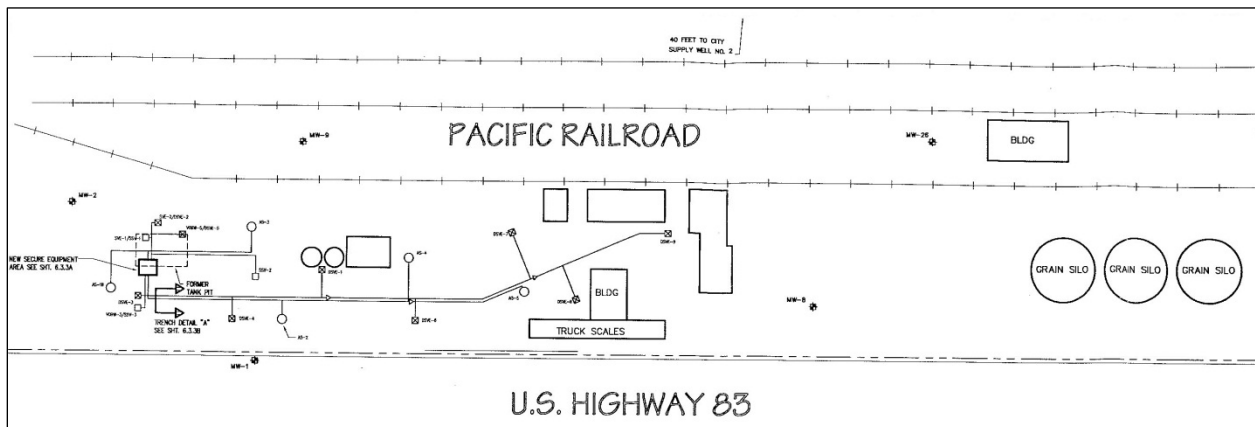
(Source: EGEI 1997)

Figure 3-3. AS/SVE Remediation Phase I



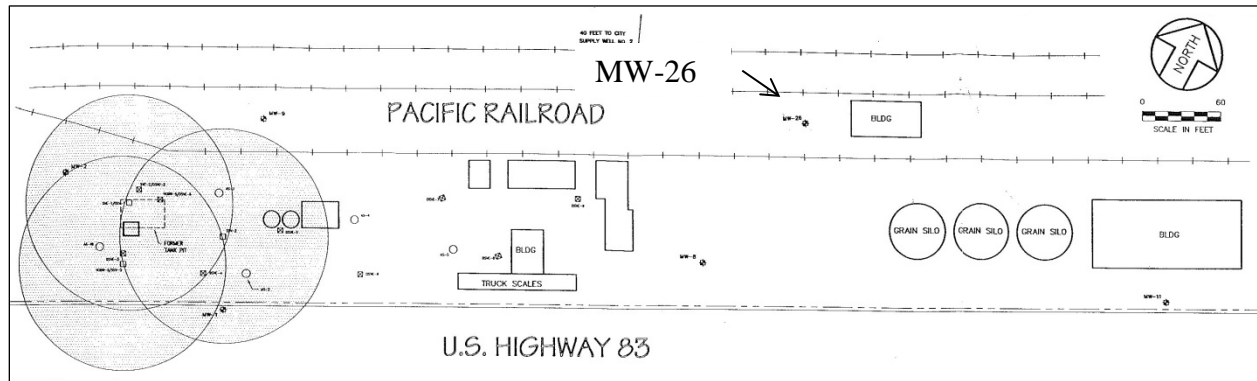
(Source: McGuire and Wilson 2010)

Figure 3-4. Remediation System Piping Plan



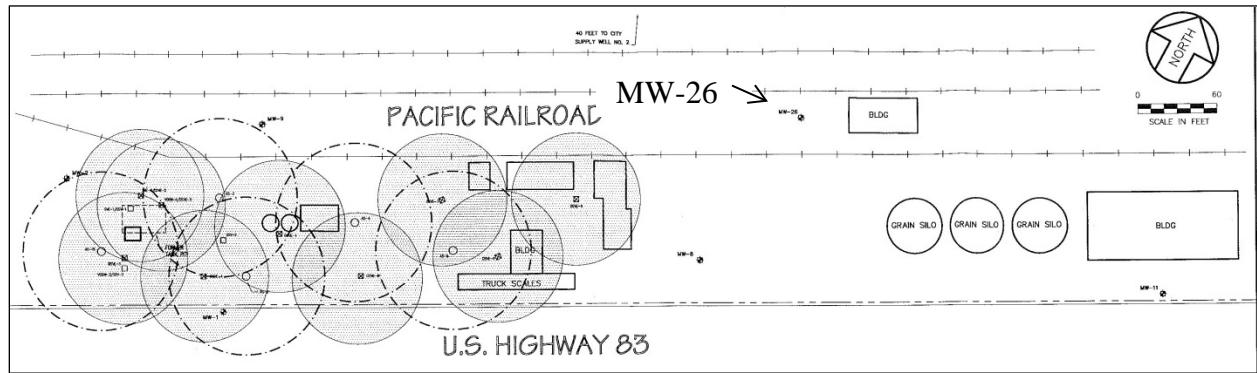
(Source: EGEI 1997)

Figure 3-5. Shallow SVE Wells Radii of Influence



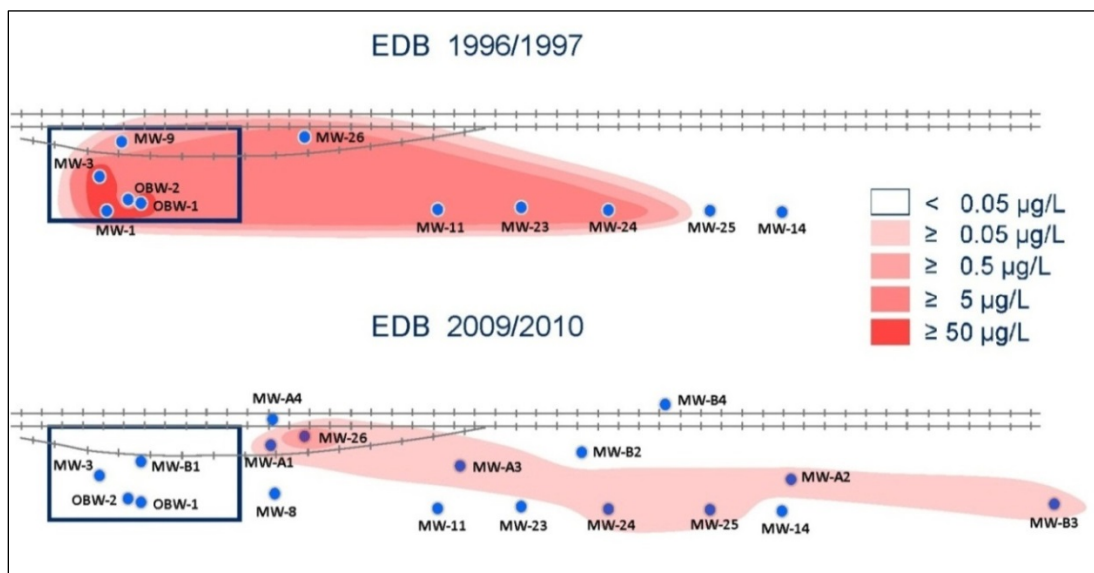
(Source: EGEI 1997)

Figure 3-6. Deep SVE Wells Radii of Influence



(Source: EGEI 1997)

Figure 3-7. EDB Concentration in Home Oil Plume 1996-2010



(Source: McGuire and Wilson 2010)

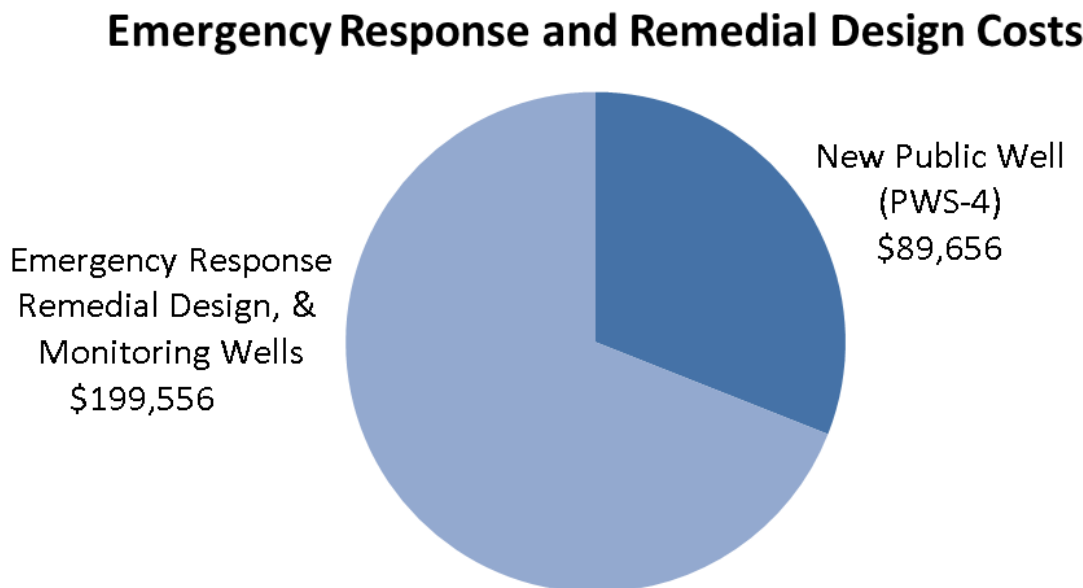
In 2010, the KDHE Trust Fund Program became aware of additional monitoring wells managed by the KDHE State Water Plan. From 2010 forward, monitoring wells MW-A1 through MW-A4 and MW-B1 through MW-B4 were sampled in addition to the site monitoring wells to track the low concentrations of EDB. Earlier sampling of the State wells, which were located outside the AS/SVE system's zone of influence, may have influenced some changes in the remedial system (McGuire and Wilson 2010).

During a phone interview with Emily McGuire, P.G., with the KDHE Storage Tank Section, she said that if the Home Oil remedial system were designed today, KDHE would have requested a minimum of 15 AS injection wells instead of the current system's 12 injection wells due to the extent of the area covered by the remedial system.

3.3.2 COSTS OF REMEDIATION TECHNOLOGIES

Costs for the new public water system well and initial emergency response, remedial design, and monitoring wells for the Home Oil site are shown in Figure 3-8. Costs to install and operate the Home Oil system from 1997 to 2013 are shown in Figure 3-9.

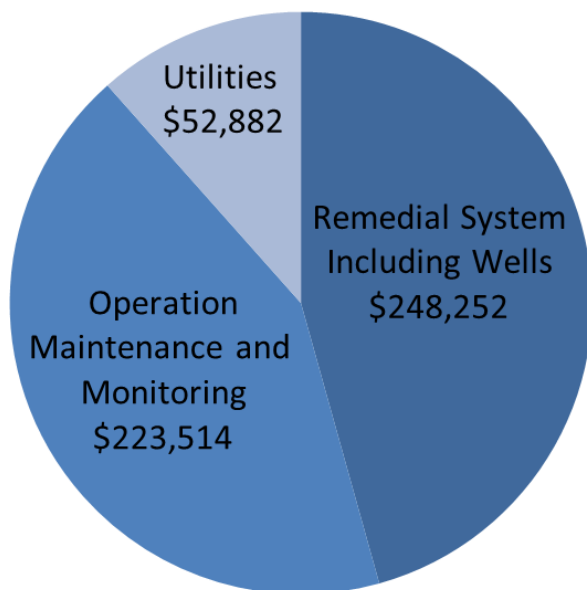
Figure 3-8. Emergency Response and Remedial Design Costs for the Home Oil Bulk Plant



(Sources: McGuire 2013b; McGuire and Wilson 2010)

Figure 3-9. Breakdown of Costs for Remediation from 1999 to 2012

Cost of Remediation from 1999 to 2012: \$543,648



(Sources: McGuire 2013b; McGuire and Wilson 2010)

The AS/SVE system has proven to be a cost effective method of remediation of the constituents of the Home Oil plume including EDB (McGuire 2013a).

3.3.3 CLEANUP STATUS/RESULTS

By 2012, EDB concentrations at the Home Oil plume site had dropped below the MCL of 0.05 µg/L and the site was considered clean for EDB. The AS/SVE remedial system installed in 1999 remains in operation to clean up the remaining 1,2-DCA.

EDB was first discovered in 1995 and concentrations in the source area (MW-1 through OBW-2) were as high as 115 µg/L in 1996. The graphs below show the decline in concentrations at monitoring wells throughout the plume. The wells presented in Figure 3-10 are in order from the source area downgradient to MW-B3, which is a Kansas state well that was only sampled from 2010 to 2013.

Conditions at the site including subsurface stratigraphy, relatively shallow depth to groundwater, and the volatility of the plume compounds increased the effectiveness of the system. Kansas continues to use AS/SVE systems to remediate EDB plumes.

3.3.1 PROBLEMS ENCOUNTERED

According to phone interview with Emily McGuire, P.G., with the Kansas Storage Tank Section, on May 2, 2013, several problems were encountered during the Home Oil remediation, but most were successfully resolved. The main problems were the screening depth of the AS injection

wells, vibrations from the large AS/SVE system, failing couplings, proximity to the grain coop, and challenges associated with sampling in winter climates.

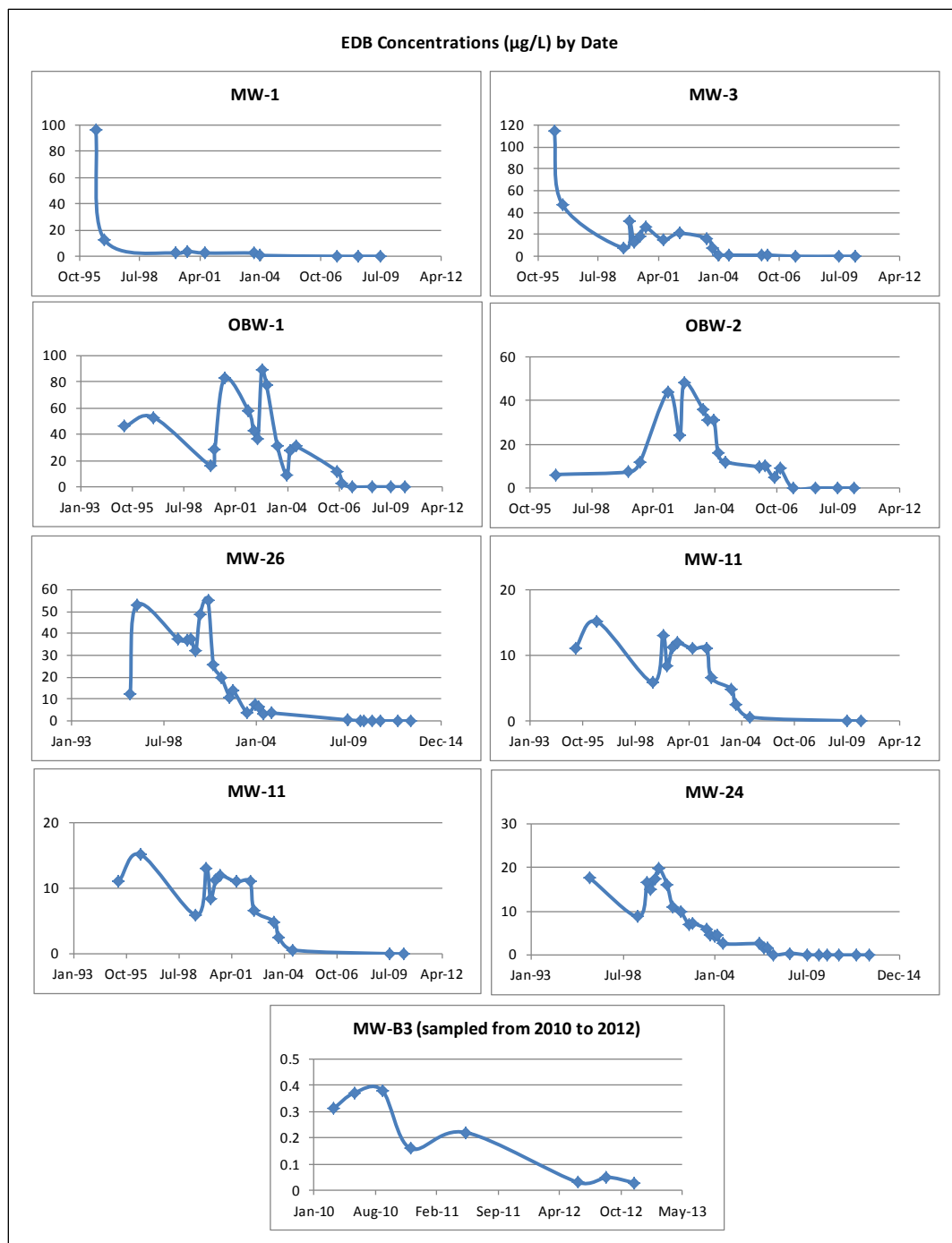
The original design of the AS/SVE remedial system called for the AS injection wells to be screened 28.5 feet below the SWL. This was due to anticipation of a steady decline in the Ogallala water levels and the characteristics of EDB in groundwater. EDB in the Home Oil plume was a component of gasoline which is considered an LNAPL. LNAPL does not readily mix with water and because it is less dense than water it tends to spread across the surface of the water table. Over a period of time, EDB will leach out of the gasoline and form a dissolved phase plume that spreads downgradient from the source area. Dissolved EDB has a higher solubility and specific gravity than other components of gasoline such as BETX. As it dissolves, it migrates below the surface of the water. In 2007, after the remedial system had been operating for eight years, Ogallala Aquifer water levels had not dropped as anticipated and low levels of EDB persisted at the site. The team deduced that the EDB had not migrated to the expected depths within the plume and decided to replace five of the AS injection wells with new injection wells screened at 12 feet below the SWL. By 2010, the plume had fallen below the MCL of 0.05 µg/L except in the vicinity of MW-26 (Figure 3-7). By 2013, EDB was detected at MW-26 at concentrations less than 0.029 µg/L, which is below the MCL (Table 3-1). By 2013, concentrations at all wells within the plume had dropped below the MCL. The site is considered clean for EDB but remains in operation today to treat low levels of 1,2-DCA.

Two of the problems encountered at the site were related to mechanical issues while other problems were related operations at the grain coop east of the site. Strong vibrations, not encountered at other sites, occasionally damaged the AS/SVE system piping and required maintenance that had not been anticipated. The vibrations were thought to be caused from the type of building housing the unit and the size of the unit. The system is housed in a stick-built wooden building, possibly preassembled or purchased through a lumber yard. More recent systems are installed in standard design metal trailers with a plywood floor and walls. Systems installed in the metal trailers have not experienced problems with vibrations. In addition to the vibrations, and possibly related, was the failure of couplings that connect the motors to the compressors in AS/SVE systems. These couplings had to be replaced several times but the cause of the failure was not identified, but may have been caused by the vibrations loosening the screws attaching the unit to the floor of the wooden building increasing stress on the couplings from shaking. Metal braces were used to attach the AS unit to the floor, which helped but did not eliminate the problem. Kansas has not experienced this type of failure at other AS/SVE sites. Another site specific problem was heavy truck traffic in the vicinity of the grain coop where several down gradient monitoring wells were located. Several of the wells in heavy truck traffic areas were damaged and had to be replaced. In addition to the damage from heavy traffic, grain piles stored on top of monitoring wells hindered the sampling effort on several occasions. A summary of major maintenance and repair work done since the systems start up can be found in the Quarterly Monitoring Report for the reporting period of December 18, 2012 through March 21, 2013 (MESI 2013).

The last problem encountered was related to winter weather conditions and is not unique to the Home Oil site. Monitoring wells covered with snow, ice, and frozen mud can be difficult to

locate, and if located difficult to open without damaging the well cover. On several occasions, wells were not sampled during the scheduled sampling event due to weather related circumstances.

Figure 3-10. EDB Concentrations in Home Oil Monitoring Wells 1995 to 2013



(Source: MESI 2013)

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4.0 DEL MONTE

4.1 DEL MONTE BACKGROUND

The Del Monte site is an approximately 6,000-acre site in Honolulu County, on the island of Oahu, Hawaii. It is surrounded by agricultural and military land (USEPA 2013a; EPA 2003b). The site consists primarily of agricultural land with two company-operated housing complexes (Kunia Village and Poamoho Village), equipment maintenance areas, pesticide storage facilities, warehouses, and administrative buildings (GAI 1999). It can be geographically divided into two main sections: (1) the Kunia Section to the south; and (2) the Poamoho Section to the north, which are separated by the Schofield Plateau drainage divide and the Schofield Barracks (USEPA 2003b). See Appendix B, Map 1 for a general site overview (USEPA 2010b).

Del Monte Corp. began growing pineapple on the site in the 1940s, using EDB as a pesticide to control nematodes, which infest pineapple root, from the early 1940s until 1983 (USEPA 2013a). On April 7, 1977 the failure of a hose on a bulk transport container resulted in the release of approximately 495 gallons of EDB containing dibromochloropropane (DBCP) within approximately 60 feet of a drinking water supply well (the Del Monte Kunia well) (USEPA 2013a; GAI 1999). In addition to these known release, the storage and mixing of pesticides at the facility is considered to have impacted soil and perched groundwater in the vicinity of the Kunia well (USEPA 2013a).

One week after the 1977 spill, the well was tested by the Hawaii Department of Health (HDOH); no contamination was detected (GAI 1999). However, after DBCP was detected in groundwater in California near fumigated farmland in 1979, a joint groundwater sampling program was initiated by the Pineapple Growers Association of Hawaii and the State of Hawaii Departments of Agriculture and Health. EDB and DBCP were detected in the Kunia well on April 14, 1980 (92 and 11 µg/L, respectively) and during a resampling event on April 24, 1980 (300 and 0.5 µg/L, respectively). The Kunia Well supplied water to the residents of Kunia Village and agricultural water to the plantation from 1946 through April 25, 1980, but use was discontinued based on the sampling results (GAI 1999).

From 1980 to 1994 Del Monte extracted groundwater using the Kunia well (deep groundwater) and three extraction wells (shallow groundwater), using contaminated groundwater for dust control on roads and unplanted pineapple fields. The practice was discontinued in 1994 at the request of EPA, citing unlawful disposal of a hazardous substance under the RCRA and CERCLA statutes (USEPA 2013a).

Following the discovery of EDB in the Kunia well, in 1981 Del Monte initiated soil and groundwater investigations to characterize the extent of contamination in the spill area. In addition to the Kunia well spill area, fumigants were detected at the Former Fumigant Mixing Area and Former Fumigant Storage Area, located within approximately 50 to 150 feet of the Kunia well. As a result, 2,000 tons of contaminated soil were removed from the EDB spill area in 1981 and 16,000 tons of soil removed from the former pesticide mixing and storage areas in 1983, resulting in the creation of a 75- by 75-foot excavation pit 60 feet deep. The excavated

soil was spread on a nearby field and the pit backfilled in October 1999 (USEPA 2003b. See Appendix B, Map 2 for a figure showing the former excavation areas (GAI 1999).

In December 1994, EPA placed the site on the NPL pursuant to CERCLA due to the 1977 EDB spill (GAI 1999). Remedial efforts are ongoing (USEPA 2013a). A September 30, 2003 ROD indicates that risks to human health and the environment due to the presence of EDB and other COCs at the site are sufficient to warrant response. The ROD states that risk characterization results show that potential cancer and noncancer risks to Kunia Village and downgradient residents within 1.5 miles of the Kunia Village Area (KVA) exceed acceptable levels, and that the presence of COCs in basal groundwater exceeds drinking water MCLs (USEPA 2003b).

Site Geology/Hydrogeology

The Island of Oahu is comprised of the remnants of the Waianae Volcano and the Koolau Volcano, two late Tertiary shield volcanoes and their associated rift zones. Lava flows from the Koolau dome produced the broad, gently sloping central area of Oahu called the Schofield Plateau. The site is located on the western side of the Oahu central plain, which stretches between the Waianae and Koolau Mountain ranges. The site is underlain by the weathered remnants of basaltic lavas and surrounded by the Waianae basalts to the west and Koolau basalts to the east. Near-surface soils are characterized by deep-red lateritic lithosol with a loose, porous structure grading to saprolite, a clay-rich, decomposed rock formed by in-situ weathering of basalt, to depths of approximately 150 feet bgs. The saprolite is underlain by basalt (GAI 1999).

Regionally, groundwater occurs within two zones: a perched (shallow) aquifer extending to approximately 100 feet bgs and a basal (deep) aquifer encountered at approximately 850 feet bgs. Water from the perched zone infiltrates down to basal groundwater, which is used for drinking water and irrigation (EPA 2013a). Perched groundwater is confined to saprolite material with relatively low permeability, above weathered basalt. Horizontally water in the perched aquifer flows to the north-northeast; vertically it flows downward, migrating through an unsaturated, highly permeable basalt sequence. Perched groundwater may be encountered at depths ranging from the surface to over 40 feet bgs depending on location and season (GAI 1999).

The basal groundwater table is typically flat and located several to several tens of feet above sea level, accumulating in a lens-shaped body with a surface above the surface of salt water due to the contrast in densities between freshwater and saltwater. The KVA overlies the Pearl Harbor Basal Water Body near the contact between the Waianae and the Koolau aquifer systems. The Kunia well appears to have been constructed in the Waianae aquifer based on hydraulic gradient data and extrapolation of known information with regard to the location of the surface contact between the Waianae and Koolau basalts (GAI 1999).

Plume Characterization

The site is defined as a 300- by 300-foot area of the perched aquifer at the KVA, and the downgradient extent of EDB and DBCP exceeding drinking water MCLs in the Waianae portion of the Pearl Harbor Basal Aquifer (GAI 1999). Historical uncontrolled releases of fumigants in

the vicinity of the Kunia well have resulted in elevated concentrations of fumigants in soil and perched groundwater; the basal aquifer contains lower levels of contaminants, but with concentrations above Hawaii MCLs (USEPA 2010b).

Soil and shallow groundwater is impacted with EDB, DBCP, 1,2 dichloropropane (DCP), 1,2,3-trichloropropane (TCP), benzene, and lindane. Deep groundwater is impacted with EDB, DBCP, and TCP (USEPA 2013a). According to the December 17, 1999 Baseline risk assessment, potential receptors at risk from EDB and other contaminants of concern (COCs) from the KVA are associated with the Waianae aquifer only, as groundwater beneath the KVA is within the Waianae portion of the Pearl Harbor basal aquifer (GAI 1999).

See Appendix B, Map 3 for a depiction of the EDB plume (GAI 1999).

History of Agency Involvement

The following list summarizes the history of agency involvement with the site:

- In 1980, Hawaii Department of Health (HDOH) began testing water wells for contaminants, including EDB. EDB and DBCP were detected at the Kunia well, which was subsequently removed from service.
- In 1997 and 1998, investigative activities were conducted to address contaminated soil, groundwater, surface water, and sediment at the site, at the spill area and in its vicinity.
- In November 1998, Del Monte Fresh Produce (Hawaii), Inc. conducted an RI under an agreement with EPA.
- In 1999 through 2000, Del Monte completed a Baseline Human Health Risk Assessment to evaluate risks to human health from potential exposure to contamination identified in the RI.
- On April 5, 2002, Del Monte completed an Addendum to the RI Report describing additional soil and groundwater sampling in the spill area.
- On May 9, 2002, Del Monte completed a Phytoremediation Treatability Study evaluating the use of plants to break down chemical contamination in perched groundwater to nontoxic compounds.
- In February 2003, Del Monte completed an RS report evaluating cleanup alternatives.
- In March 2003, EPA issued a Proposed Plan describing EPA's preferred cleanup method based on its analysis of the FS. In September 2003, EPA issued a ROD describing the selected remedy, a two-part system addressing contamination in (1) the perched aquifer and deep soil, and (2) the basal aquifer.
- On January 13, 2004, EPA delisted the Poamoho section of the site from the NPL based on the results of an investigation published in a March 17, 2003 RI Technical Memorandum indicating that this area posed no significant threat to human health or the environment.

- On September 25, 2005, a Remedial Design/Remedial Action Consent Decree with Del Monte Fresh Produce (Hawaii) was filed with the United States District Court, District of Hawaii, requiring Del Monte to design and construct a vegetated soil covering (cap) and SVE system.
- On September 18, 2007, an Institutional Controls Consent Decree was filed with the District Court, restricting land use in the Kunia Village Area and requiring Del Monte to take measures to protect the public from exposure to contaminated soil and groundwater. The Consent Decree established a “well restriction area” restricting Water Use Permits without prior written approval from EPA, and ensures that EPA will have access to monitoring and treatment equipment facilities during remediation.
- On June 14, 2010, EPA finalized its Five-Year Review Report for the site, which evaluates the implementation and performance of the selected remedy. The Five-Year Review Report concluded that while concentrations of EDB and other contaminants were detected above Hawaii MCLs in basal aquifer groundwater at the site, the remedy was found to be protective of human health and the environment (HHE) because there is no receptor exposure to untreated perched or basal aquifer groundwater (USEPA 2010b; USEPA 2013a).

4.2 EDB CONCENTRATIONS IN CONTAMINATED MEDIA

One week after the April 7, 1977 release of 495 gallons of EDB containing DBCP, no contamination was detected in the Kunia well. However, during a joint groundwater sampling program EDB and DBCP were detected in the Kunia well on April 14, 1980 (92 and 11 µg/L, respectively) and April 24, 1980 (300 and 0.5 µg/L, respectively) (GAI 1999).

Sampling was conducted in 1997 and 1998 to delineate EDB and other COC impacts to soil and groundwater, submitted in a 1999 RI and a 2000 Baseline RA. Three “known” sources of EDB contamination were identified during the 1997-1998 RI in the KVA, including the Kunia Well Spill Area, the Former Fumigant Storage Area, and the Former Fumigant Mixing Area. Other Potential Source Areas were also investigated but no EDB impacts were noted (GAI 1999). Based on the results of the RI and Baseline RA, areas requiring response action include subsurface soils greater than 20 feet bgs in the Kunia Village source area, the perched aquifer in the Kunia Village source area, the basal aquifer in the Kunia Village source area, and the basal aquifer plume that has migrated downgradient of the source area. No COCs were detected above preliminary remediation goals (PRGs) (now called Regional Screening Levels (RSL)) in the Poamoho Section of the site (approximately 3 miles north of the known source area) (USEPA 2003b).

The following media were investigated:

- Soils OU: low concentrations (below residential PRGs) of EDB were detected in surface and vadose zone soils in the KVA. Soil vapor modeling results indicated that EDB in ambient air was well below levels of concern.

- Surface Water and Sediment: EDB was detected in surface water associated with an ephemeral stream gulch northeast of the KVA at 170 µg/L, and in a grab sample from the excavation pit at 167 µg/L. An earthen berm was constructed to prevent stormwater runoff from the excavation pit, and later backfilled as approved by EPA. EDB was not detected in sediment and soil runoff samples.
- Groundwater OU: EDB was detected in the perched groundwater zone and basal aquifer in the KVA and downgradient plume.
- Perched aquifer: EDB was detected at an average concentration of 3,227 µg/L. The RI indicates that variation in concentrations of contaminants likely reflected the variety of operations that took place in each area, and represented spills that took place at different times.
- Basal groundwater: EDB was detected at concentrations from 0.13 to 0.22 µg/L in the Kunia Well, and 0.1 to 0.26 µg/L in the Basal well. Modeling of EDB based on sampling data indicated that the basal groundwater layer impacted by infiltrating chemicals is approximately 1 to 10 feet thick near the water table surface directly beneath the perched aquifer source area. EDB concentrations up to 0.025 µg/L were reported in regional basal wells.

The RI concludes that the only significant source of chemicals to the basal aquifer area is area-wide infiltration of perched aquifer groundwater in the immediate vicinity of the KVA. EDB was not detected during sampling of other potential source areas. See Appendix B, Maps 4A-4E for soil and groundwater sampling locations, and the RI for the complete analytical data (GAI 1999).

Additional dynamic sampling of the Kunia and Basal wells was conducted during a 10-day pump test from July 27, 1998 to August 6, 1998. The pump test confirmed previous conclusions suggesting that the capture zone is approximately equal to the dimensions of the source zone; after approximately three days of pumping the groundwater capture zone will expand beyond the size of the source zone and relatively clean water is pulled toward the well and concentrations of EDB decline. See the RI for complete pump test sampling data (GAI 1999).

As described in the 12/17/1999 Baseline RA, two boreholes (TB-7A and TB-8A) were advanced in the perched aquifer zone for the purpose of being completed as perched aquifer extraction wells to support the phytoremediation treatability investigation. An additional twelve extraction wells were advanced in the Former Fumigant Storage Area for source removal and hydraulic containment objectives of the pilot phytoremediation studies (GAI 1999).

4.3 REMEDIATION TECHNOLOGIES USED

As discussed in the September 30, 2003 ROD, EPA evaluated the following potential remedies for the site:

- Perched aquifer: P1) No action; P2) groundwater extraction and treatment with capping; and P3) groundwater extraction and treatment with capping and soil vapor extraction.

- Basal aquifer: B1) No action; B2) phased groundwater extraction and treatment with contingent monitored natural attenuation; and B3) groundwater extraction and treatment in the source area and the downgradient plume.

EPA evaluated these options using a comparative analysis requiring that the selected remedy provides adequate protection of human health and the environment and is compliant with appropriate federal and state requirements, standards, criteria, and limitations. Other criteria taken into consideration included long-term effectiveness and permanence, showing that the remedy maintains reliable protection of human health and the environment over time; reduction of toxicity, mobility, or volume through treatment; short-term effectiveness, addressing the amount of time needed to implement the remedy and any adverse impacts posed to workers and the community during construction and operation; implementability of the remedy with regard to technical, design, construction, and operational considerations; and cost. State and community acceptance were also taken into account when choosing the remedy (USEPA 2003b)

Perched Aquifer: Selected Remedy

Perched aquifer alternatives P2 and P3 were found to be adequate with regard to meeting RAOs. Perched aquifer alternative P3 was ranked higher than P2 due to the additional contaminant removal by using the SVE and was thus the selected remedy.

The selected perched aquifer remedy included the following major components:

- Backfilling the pit (already completed);
- Construction of a soil cap over the most impacted area of the perched aquifer;
- Installation of a groundwater extraction system to hydraulically contain the mass flux of COCs to the basal aquifer and to depress the water table for SVE;
- Treatment of extracted groundwater via phytoremediation and/or physical treatment;
- Installation of a SVE system in the most impacted area of the perched aquifer;
- Implementation of institutional controls to prevent exposure to impacted groundwater and soil and to prevent activities which may interfere with the remedy;
- Operation of the groundwater extraction and treatment and SVE systems until the perched aquifer's impact on the basal aquifer reaches RAOs;
- Monitor groundwater until remediation goals are achieved and maintain effectiveness over time;
- Monitoring cap maintenance and inspection monitoring until remediation goals are achieved and monitoring of basal groundwater complete; and
- Maintenance of institutional controls until RAOs have been met (USEPA 2003b).

Under remedy P3, a vegetative soil cap and stormwater drainage system were constructed to extend across the entire perched aquifer source area. The vegetative cover was established

between August and October 2008 and was originally irrigated to maintain the vegetative cover. Visual monitoring is conducted on a weekly basis and after larger rain events as part of long-term O&M, to verify the integrity of the cap, the status of fencing and signage, to verify that standing water is not present on the cap, and to monitor for settling or excessive erosion of the cap. Debris is also removed from the diversion ditch (GAI 2013a).

Extraction and treatment of perched groundwater began in 1998 and gradually expanded through 2008 as the source area was delineated. Between 1998 and 2001, 35 perched groundwater extraction wells and 21 monitoring wells were installed throughout the source area, and a lined, closed-loop phytoremediation system was constructed for treatment of extracted perched groundwater. The phytoremediation system collected excess water in sumps fitted with pumps to recirculate water through drip irrigation to the phytoremediation trees. Irrigation of the trees was supplemented with potable water during drier months. During periods of heavier rains the phytoremediation system was shut down temporarily, as it was unable to receive extracted perched water. Water levels for the extraction wells were taken on a biweekly basis. Extraction water from individual wells was pumped to a holding tank called the “white tank” and then pumped to the phytoremediation cells (GAI 2013a). Figure 4-1, below, shows the perched groundwater extraction wells.

Figure 4-1. Perched Groundwater Extraction Wells



(Source: USEPA 2008b)

In 2008 the full-scale perched groundwater extraction and treatment system was completed. The full-scale system included the reconfiguration of existing extraction and monitoring wells to serve as SVE wells, groundwater extraction wells, dual phase groundwater/SVE-extraction

wells, or monitoring wells. Three additional monitoring wells and seven additional extraction wells were installed at this time. Extracted groundwater is pumped to the white tank at a rate of approximately 20 gpm. At least once a week perched groundwater is pumped from the white tank to the phytoremediation system via a 5-horsepower pump. Extracted groundwater is also routed to the phytoremediation system when the well treatment system is offline for maintenance (GAI 2013a).

Del Monte has operated and maintained two phytoremediation treatment units in the source area since 1998. Contaminated groundwater from the perched aquifer is pumped to two closed-loop treatment cells planted with Koa haole plants (*Leucaena leucocephala*), which degrade contaminants to nontoxic compounds. Two small phytoremediation cells were removed in 2008 to make room for an SVE system and soil cap, but the large unit is still in operation. In the event of overloading of the system during heavy storm events, water can be redirected to the basal groundwater treatment system (USEPA 2013a). Figure 4-2, below shows the perched aquifer treatment system.

Figure 4-2. Perched Aquifer Treatment System Pad



(Source: USEPA 2008b)

The SVE system consists of SVE and dual SVE/groundwater extraction wells grouped by spatial distribution and connected through a series of nine separate SVE pipe headers. The headers combine at a central manifold located on the perched aquifer treatment system equipment pad, which branches to two liquid ring vacuum pumps. The blowers can be run in tandem or individually. SVE off-gas from the blowers passes through an oil demister and then through two 2,000-pound GAC vessels that remove organic compounds from the off-gas. Three stages of SVE monitoring are conducted: SVE system startup, routine performance monitoring, and post

shut-down conformational monitoring. SVE system startup was initiated on June 20, 2008, starting with areas that were dewatered and gradually increasing to include additional areas. The startup sequence was complete by October 9, 2009, after which normal operation began. Routine performance monitoring includes monthly SVE off-gas sampling, monthly or weekly vacuum monitoring and flow rate recording, and quarterly SVE off-gas sampling. SVE off-gas is sampled at active headers, between blower and carbon treatment, between carbon vessels, and after carbon treatment. In addition, vacuum, off-gas and flow rate monitoring is conducted as needed at each header and in active SVE wells. The SVE extraction system allows selective extraction from groups of wells with rotation of treatment between well groups, determined through professional judgment and site data (GAI 2013a). See Figure 4-3, below, for SVE blower and carbon treatment system.

See Appendix B, Maps 5A-5B for perched aquifer remediation system details and well locations (GAI 2013a).

Figure 4-3. SVE Blowers and Carbon Treatment Vessel System



(Source: USEPA 2008b)

Basal Aquifer: Selected Remedy

Alternatives B2 and B3 were found to be adequate for addressing basal aquifer contamination; however B2 was the selected remedy based on the additional costs anticipated for B3. The selected basal aquifer remedy included the following major components:

- Installation of groundwater monitoring wells to characterize the plume and monitor performance;

- Extraction of basal groundwater in the source area;
- Implementation of a groundwater monitoring program;
- Increasing the pumping rate from the Kunia Well and/or other wells as needed to attain source control;
- Evaluation of data and consideration of contingency for monitored natural attenuation;
- If natural attenuation proves ineffective, implement additional pumping and treating of the downgradient plume;
- Implementation of institutional controls to prevent exposure to impacted groundwater and interference with the remedy; and
- Continued institutional controls and monitoring for at least five years after groundwater cleanup levels have been achieved to ensure that concentration levels are stable and remain below MCL.

Per the ROD, the basal groundwater system would be implemented as follows:

- Basal groundwater extraction would be implemented first in the source area, and would be intended to work as a hydraulic containment to prevent migration of COCs outside of the source area. Additional extraction would be performed as needed based on the effectiveness of the remedy.
- Physical treatment of extracted groundwater would consist of air stripping followed by liquid phase carbon adsorption. A packed tower air stripper would be used, as it reportedly provides better air-water contact than a tray stripper and is therefore more efficient.
- MNA is the monitored use of naturally occurring physical, chemical, and biological processes to reduce toxicity, mass, mobility or concentration of COCs without human intervention. The primary MNA remedy at the site was expected to be dispersion with some abiotic degradation.
- Institutional controls would prohibit certain activities at the site without approval from EPA in order to prevent interference with selected remedies.
- Monitoring of the basal aquifer would include installation of groundwater monitoring wells to characterize the plume and assess the effectiveness of the source control remedies. Monitoring wells would be installed in a phased approach, including two wells installed near the Basal well and Kunia well, a monitoring well installed to delineate the extent of the basal aquifer source area and monitor performance of the source area containment system, wells installed in the downgradient flow path once it has been determined using existing wells, and additional wells installed on an as-needed basis (USEPA 2003b).

Del Monte has operated the basal groundwater treatment system, the Kunia Well Treatment System since September 14, 2005. During the initial startup, samples were obtained daily for

five days, then weekly for one month. Subsequent samples have been obtained monthly from the following:

- Influent samples from the Kunia Well prior to routing it to the air stripper;
- Sample obtained just after the air stripper;
- Effluent sample obtained after water is routed through the carbon treatment vessel.

In addition, monitoring of basal groundwater monitoring wells is conducted quarterly. See Appendix B, Maps 6A-6B for basal groundwater sampling locations (GAI 2009).

4.3.1 EFFECTIVENESS OF REMEDIATION TECHNOLOGIES

The removal of the Kunia well from service and excavation of 18,000 tons of soil in the early 1980s reduced immediate threats to human health and the environment (USEPA 2013a). Subsequently, the following RAOs were set for the site as part of the September 30, 2003 ROD: prevention of exposure of the public to contaminated groundwater above chemical-specific cleanup levels; inhibition of further migration of the contaminant plume; limitation of discharge of KVA groundwater and deep soil contaminants to basal groundwater; and restoration of basal groundwater to its beneficial use of drinking water supply within a reasonable timeframe (USEPA 2003b).

As of the most recent available Perched Groundwater Remedial Action Report, dated February 20, 2013, COC concentrations detected in perched aquifer samples obtained since the beginning of full-scale remediation in July 2008 have been steady or slightly decreasing, but a high degree of variability in COC concentrations was noted in some wells. In addition, the SVE system had removed a calculated estimate of 0.491 kilogram (kg) of EDB. Vacuum readings indicate that the SVE system is achieving inward pressure gradients throughout each active treatment area and beyond, and that the system continues to extract and capture COCs.

See the Remedial Action Report for complete analytical data showing EDB trends since the start of the perched groundwater remedy (GAI 2013a).

The most recent available Basal Groundwater report, dated January 24, 2013, shows that concentrations of EDB detected in the Kunia well and well BMW-1 prior to 2001 were significantly higher than concentrations detected since 2005. Since the start of the full-scale perched groundwater remediation system in 2008, concentrations of EDB detected in the Kunia well and basal monitoring wells have shown slight reductions or remained constant, with the exception of one well (BMW-4), which fluctuate. As of January 7, 2013, the Kunia Well Treatment System treated approximately 1.7 billion gallons of water. All effluent sampling results during the most recent quarter were below laboratory detection limits (GAI 2013b).

See the October 2010 Quarterly Basal Groundwater Monitoring Report for analytical data showing EDB trends since the start of the basal groundwater remedy (GAI 2013b).

In addition, in its summary of the Del Monte site, EPA notes that contaminant concentrations in shallow groundwater have decreased from hundreds of parts per billion (ppb) to tens of ppb. In addition, deep groundwater has been treated to below safe drinking water standards since 2005 (USEPA 2013a).

A September 8, 2008 Preliminary Closeout Report indicates that additional monitoring and completion of the pump and treat cycle are projected to continue through 2018 (USEPA 2008b).

4.3.2 COSTS OF REMEDIATION TECHNOLOGIES (IF AVAILABLE)

The original cost estimate for implementing the ROD was \$9.9 million for the basal aquifer and \$3.0 million for the perched aquifer, with annual O&M of \$7.17 million. According to the Preliminary Closeout Report the basal aquifer remedy was constructed for approximately \$3.5 million and the perched aquifer for \$1.5 million. EPA oversight costs were \$89,000 for construction and \$9,000 per year for annual maintenance activities (USEPA 2008b).

4.3.3 CLEANUP STATUS/RESULTS

According to EPA's June 2010 five-year review, the remedy for the site is protective of HHE because there is no exposure to untreated perched or basal groundwater. In addition, the HDOH has placed restrictions on the site for use of any basal groundwater without treatment unless the groundwater meets State of Hawaii MCLs. The five-year review also found that the remedy for the site was constructed in accordance with the requirements of the ROD, and is functioning as intended by the decision document with one exception related to the basal aquifer remedy. According to the review, the ultimate objective for the basal aquifer remedy is to restore the basal aquifer to its beneficial use as a drinking water source. However, groundwater data indicates that background levels of COCs in the basal aquifer are present in concentrations above Hawaii MCLs due to historical pesticide use. The five-year review therefore states that at some point in the future, this RAO and cleanup levels of Hawaii MCLs for the basal aquifer may need to be re-evaluated (USEPA 2010b).

The ROD states that monitoring of perched groundwater would be conducted until the RAOs are achieved, and would include monitoring extraction wells and monitoring wells including those installed for the phytoremediation study and monitoring soil and groundwater in the phytoremediation system to track potential buildup of COCs in soil. The duration of monitoring for Remedy P3 to achieve the RAOs was estimated to be 10 to 15 years (USEPA 2003b).

The timeframe for perched aquifer remediation was considered an uncertainty with remedy P3, as the lack of pilot testing data, and unknown extent of diffusion due to varying permeability in soil provide complicating factors (USEPA 2003b).

Based on plume modeling for the basal aquifer, the source control techniques were expected to rapidly disperse the downgradient plume, with the maximum concentrations falling below the MCL after approximately three years. Once source control is attained, MNA was projected to achieve RAOs for the basal aquifer within three to five years (USEPA 2003b).

A September 8, 2008 Preliminary Closeout Report indicates that EPA found that all construction activities for the Del Monte site had been performed in accordance with Close out Procedures for NPL sites, and that the potentially responsible party (PRP) had constructed the remedy in accordance with remedial design plans and specification. The report states that the PRP initiated activities necessary to achieve performance standards and site completion. Additional monitoring and completion of the pump and treat cycle are projected to continue through 2018 (USEPA 2008b).

4.3.4 PROBLEMS ENCOUNTERED

Problems encountered during remediation appear to be limited to mechanical issues that have arisen at various points throughout the course of operation of the groundwater extraction system, at which time the wells were removed from service for repair or discontinued (GAI 2013a; GAI 2013b).

In addition, the ultimate objective for remediation of the basal aquifer, to restore the basal aquifer to its beneficial use as a drinking water source, may need re-evaluation as groundwater data indicates that background levels of COCs in the basal aquifer are present in concentrations above Hawaii MCLs due to historical pesticide use (USEPA 2010b).

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5.0 HASTINGS GROUNDWATER OU6

5.1 HASTINGS BACKGROUND

The City of Hastings is located in Adams and Clay Counties in Nebraska. The city is home to approximately 24,000 people. Farms and pastures surround the urban area, and there are numerous private and public wells within a three-mile radius of the city. Groundwater is used to irrigate crops, for livestock, and for home and business use. There is a nearby stream and lake used for recreation (USEPA 2012b).

Beginning in 1983, the State of Nebraska began to investigate volatile organic compounds (VOCs) in Hastings' city water supply (USEPA 2012b). Groundwater contamination was identified, and consequently the contaminated area was added to the NPL on June 10, 1986 and designated the Hastings Ground Water Contamination Site. This CERCLA (Superfund) site includes properties within the central industrial area of the City of Hastings and properties east of the city limits, including a former Naval Ammunition Depot (USEPA 2012b; EPA 2005). Due to the size and complexity of the Superfund site, it has been divided into seven subsites and 20 OUs for investigation and remediation (USEPA 2012b; EPA 2007a; EPA 2013b). EDB contamination was found at the FAR-MAR-CO Subsite ("the subsite") located on the eastern edge of the city of Hastings, which is OU6 (USEPA 2007a). OU6 is actually broader in scope than just EDB contamination, as it focuses on all groundwater contamination associated with the subsite (USEPA 2007b). See the Appendix C, Map 1 for a depiction of the subsite in relation to nearby features (SSPAI 2013).

Since at least the 1950s, the subsite has been used for the storage and handling of agricultural products, primarily grains. From 1953 through 1975, the subsite was owned by Morrison-Quirk for use as a grain merchandising business. During Morrison-Quirk's tenure at the facility, the company used a liquid grain fumigant, Max-Kill10, containing CT and EDB (USEPA 2005; EPA 2007a; SSPAI 2008). FAR-MAR-CO, Inc. purchased the property in 1975. FAR-MAR-CO and its successor, Farmland Industries, also used a grain fumigant containing CT and may have used EDB (USEPA 2007a). As of 1991, the property was purchased by Cooperative Producers, Inc. for use as a grain storage facility, a facility use that has continued until at least 2007 (USEPA 2005; USEPA 2007a).

Spills and Releases

EDB from grain fumigants has entered soil and groundwater as a result of several means. First, grain fumigants would have seeped into the soils and groundwater as a result of their use (USEPA 2012b). Second, it is believed that during the 1950s to the 1970s, small amounts of Max-Kill 10 may have been poured directly onto the soil to drive rats out of their holes. Third, unknown quantities of grain fumigants were spilled onto the soil (SSPAI 1993). One such spill occurred as the result of a grain dust explosion in 1959, which resulted in the release of 997 gallons of liquid grain fumigant. Other significant spills of liquid grain fumigant likely occurred during Morrison-Quirk's operations at the subsite, especially given the mass of contaminants that have since been removed (USEPA 2005; USEPA 2007b; USEPA 2012b).

When spills of liquid grain fumigant containing CT and EDB occurred, the liquid would migrate downward in the soil through the unsaturated zone. Some of the spilled liquid adsorbed to soils above the water table while the remainder migrated to the saturated zone, where it became a source of groundwater contamination as it gradually dissolved into the groundwater and then migrated in a generally eastward direction with the groundwater (SSPAI 2010; SSPAI 2008).

Investigations have indicated that soil contamination at the subsite is generally limited to locally impacted areas surrounding the areas of release. Groundwater, however, is contaminated beneath the subsite and downgradient of it (SSPAI 1993). Groundwater entering and leaving the subsite area is also contaminated with other organic solvents from upgradient, unrelated sources. TCE contamination is present, which originated from the Colorado Avenue and North Landfill subsites of the Hastings Groundwater Superfund Site. Other groundwater contaminants also include 1,1,1-TCA and 1,1-dichloroethene (DCE) (SSPAI 2008).

Site Geology/Hydrogeology

The subsite is underlain by what is informally referred to as the Pleistocene aquifer. It is comprised of medium to very coarse, unconsolidated gravelly sand, consisting mostly of mixed lithic fragments and generally containing trace amounts of silt and clay. Thin zones of well-sorted, fine-grained quartz sand are not uncommon (SSPAI 2010).

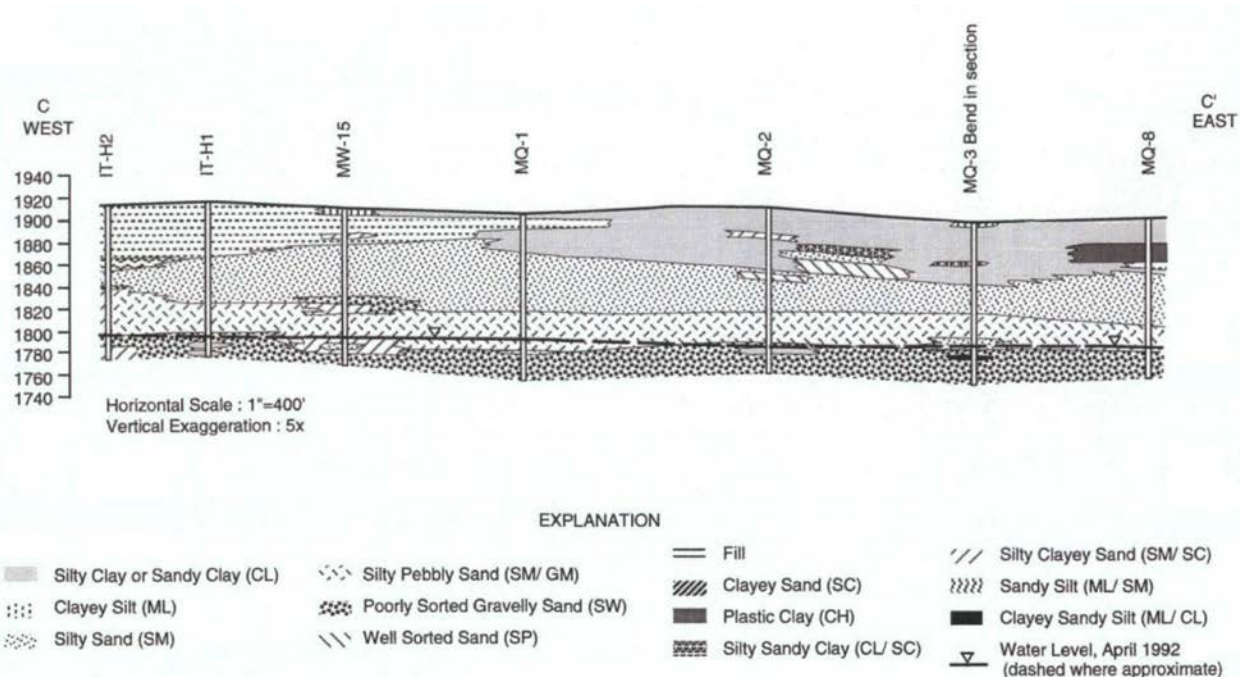
It is believed that the saturated zone is approximately 100 feet thick. Groundwater is encountered at a depth generally ranging from 120 to 130 feet bgs. The direction of groundwater flow is generally easterly. However, the direction varies seasonally, from slightly northeastward to slightly southeastward as it is affected by local pumping. The aquifer is unconfined and is fairly homogenous without major vertical barriers to flow. Transmissivity is relatively high, and the groundwater gradient is low. The horizontal hydraulic gradient across the subsite is on average about 0.0015 foot/foot under normal conditions, and the aquifer transmissivity is approximately 20,000 feet/day (SSPAI 2010). The hydraulic conductivity is approximately 230 feet/day, with an approximate linear flow rate ranging from 400 to 470 feet/year (Hydro-Trace, Inc. (HTI) 2002).

A landfill site, referred to as the North Landfill, is located about 1,000 feet upgradient from the subsite. In landfills anaerobic conditions are typical being created as organic wastes decompose and because landfill leachates are often highly reducing. Measurements at various wells indicate that conditions in parts of the subsite are reducing due to influence of leachate from the landfill site. Dissolved oxygen (DO) and nitrate concentrations are lowest close to the landfill site, and increase with distance east along the groundwater flow direction (SSPAI 2010). Figure 5-1 represents a cross-section of the aquifer underlying the subsite.

Plume and Contamination Characterization

The source area is about 75 feet wide and 100 feet long. It may contain some residual mass of adsorbed contamination that serves as a source of EDB and CT to shallow groundwater. The highest levels of dissolved contamination reside in a relatively thin layer at the water table, in shallow depths of approximately the top five feet of the aquifer (Cohen 2009a).

Figure 5-1. Cross-section of the Aquifer Underlying the FAR-MAR-CO Subsite



(Source: SSPAI 2010b)

Multiple groundwater contamination plumes are detected downgradient of the subsite. One is located at the north side of the subsite and primarily contains CT and EDB. The other plume is located at the south end of the subsite and primarily contains TCA. A third plume is located upgradient of the site that contains TCE, TCA, and PCE (SSPAI 1993).

The plumes of groundwater contamination from CT and EDB form slightly southeastward-trending lobes that extend more than two miles downgradient in the regional direction of groundwater flow (HTI 2002; SSPAI 2013). CT and EDB commingle with other contaminants, mostly notably TCE, that originated from other sources within the Hastings Groundwater Superfund Site (SSPAI 2013).

5.2 EDB CONCENTRATIONS IN CONTAMINATED MEDIA

Initial Measurements of EDB and Other Contaminants in Soil and Groundwater

Beginning in 1983, fieldwork was conducted to characterize the nature and extent of contamination at the subsite. This was achieved through sample collection from soil borings, soil-gas probes, SVE well borings, well borings, and an extraction well boring (USEPA 2007b; HTI 2004; WCC 1987).

A 1983 investigation carried out by the State of Nebraska showed EDB concentrations between 1.3 and 1.7 $\mu\text{g/L}$ at well 24, located downgradient of the subsite (WCC 1987). More extensive investigations were conducted in 1985 and 1986. Results of the soil gas survey led to the identification of two zones of contamination. The primary contaminants detected in Zone 1 soil

gas were CT and PCE while in soil it was EDB and CT. In Zone 2, the principal soil gas contaminants were PCE and TCA while the primary soil contaminants were PCE and TCA (SSPAI 1993). EDB was only detected in soil at one location, SB-16, at concentrations as high as 12,400 µg/kg at a depth of 4-6 feet bgs suggesting a localized source of EDB contamination. The 1985-1986 sampling also showed that EDB and CT were found in groundwater onsite and downgradient at levels above the MCL (USEPA 2007a; USEPA 2005). EDB concentrations downgradient decreased with distance from the subsite. Further, EDB was not detected at upgradient wells. These investigation results suggested that the source of EDB contamination in the groundwater was from the subsite, and specifically from the immediate area of soil boring SB-16 (WCC 1987).

Through the years, many additional monitoring wells were installed to better characterize the groundwater plume. As of September 1986, the highest concentration of EDB detected in groundwater was 6.8 µg/L. In 1992, the highest concentration of EDB detected in groundwater was 511 µg/L. In 1997, EDB was detected at concentrations as high as 463 ppb in well MW-08. In 2001, EDB was detected at concentrations as high as 353 ppb (USEPA 2005). The groundwater monitoring results showed that the highest concentrations of EDB in the aquifer were located on the easternmost edge of the subsite, in a narrow, east-southeastward-trending band of groundwater that extended downgradient approximately 4,500 feet. Furthermore, the results showed that EDB had migrated through the unsaturated zone and entered the groundwater system at the subsite, after which the contaminants migrated downgradient as dissolved constituents. The groundwater zone in which EDB exceeded target levels trended east-southeast, which is the same general direction as regional groundwater flow (SSPAI 1993).

Well D, which is an important well because it later became a groundwater extraction well for remediation, became operational in mid-1997. A 2002 report containing data collected from Well-D during the prior five years showed that EDB concentrations varied on an annual cycle. When the water table was drawn down from seasonal irrigation pumping, typically occurring during the third quarter sampling events, the concentrations would peak. However, when the water table was high, typically during the second quarter sampling events, then concentrations of EDB were relatively low. As the water table would rise and fall in response to seasonal ground water variations, the contaminated zone of water would move in and out of the well's screened area. This resulted in observed variations of contaminant concentrations. This was also observed in other wells, such as MW-08 in which peak concentrations of EDB in September 2002 were approximately one-third the peak concentrations reported in 1996, although the levels of EDB remained at approximately 350 to 3,500 times the MCL. The annual cyclic fluctuations have lessened as regional water levels fell. Furthermore, the cyclical pattern shown by this data could be the result of EDB as a thin film at or near the ground water surface (USEPA 2005; SSPAI 2010).

EDB concentrations at well MW-08 ranged from 86 to 302 µg/L in 2004 (SSPAI 2010). In June 2004, groundwater sampling of MW-08 was conducted using passive diffusion bags in the sample collection. Data showed significantly lower levels of EDB than were reported when using routine sampling methods. However, this data was not adequate for EPA to make a

determination regarding whether the EDB mass was present at the subsite plume only as a thin layer near the well screen (USEPA 2005).

Between late 2005 through 2009, concentrations of EDB in well MW-08 declined by orders of magnitude independent of the seasonal cycle. Since June of 2006, the concentration of EDB in well MW-08 has not exceeded 2.3 µg/L. This is about two orders of magnitude lower than the maximum concentrations measured in 2004. This change in the EDB concentration is attributed to a depletion of EDB released from the source area west of well MW-08 (SSPAI 2010). As a result, in May 2008, the Statement of Work was amended to reduce the frequency of irrigation well sampling and a Geoprobe[®] transect was added (Gresham 2010).

As of 2011, the EDB concentration in MW-08 at the subsite was 0.91 µg/L (Gresham 2011b). In July 2012, the Settling Defendant requested to terminate its monitoring and groundwater extraction requirements pursuant to performance standards. Although EPA did not consent to this request, it did reduce the number of wells and sampling frequency required (Gresham 2012d).

5.3 REMEDIATION TECHNOLOGIES USED

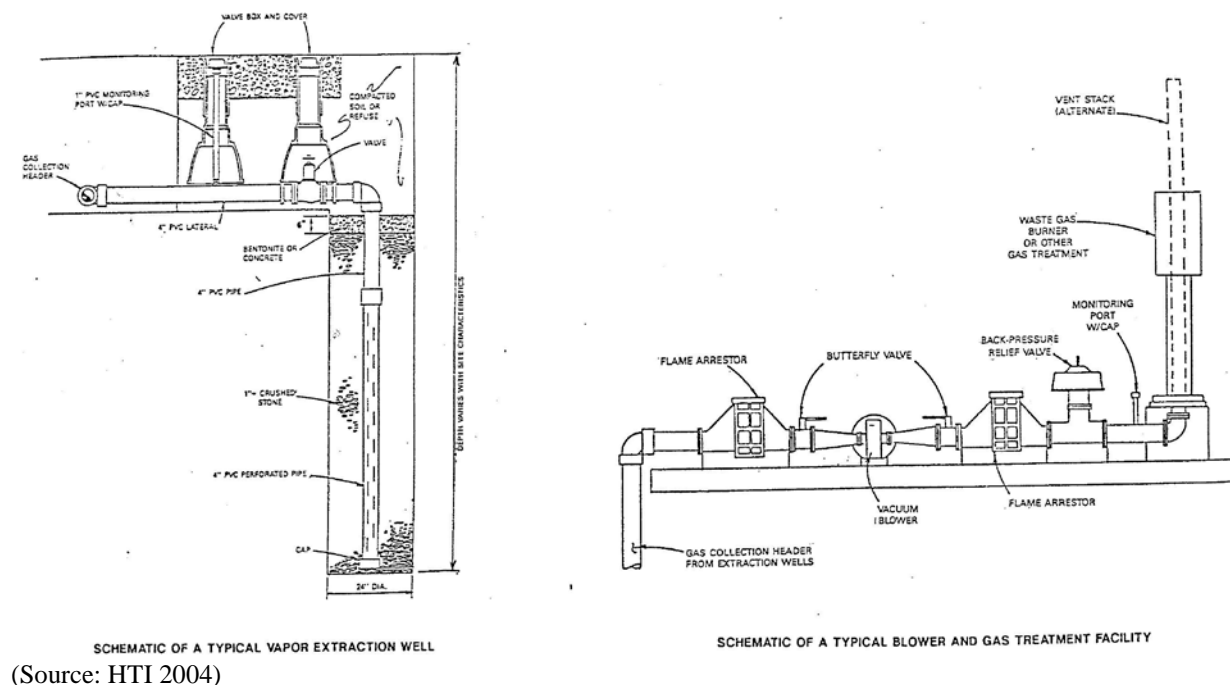
Soil Vapor Extraction

According to a ROD dated September 30, 1989, SVE was chosen to address the commercial grain fumigant contamination in soils for OU3. A SVE pilot test was then conducted in 1990 to confirm the effectiveness of removing CT and EDB from the soils. The pilot test resulted in the removal of a total of 354 pounds of EDB (USEPA 2007b; USEPA 2012b).

The nature of the SVE system actually used is unknown. However, plans for the original SVE system described it as consisting of centrifugal blowers, inflow and extraction wells, and a collection headers and gas treatment system. The blower facility was to consist of a vacuum blower, regulating valves and safety devices. Inflow and extraction wells were to consist of drilled boreholes, 12 to 36 inches in diameter, that were backfilled with pea gravel and 2- to 6-inch diameter piping. It was expected that vapor treatment would be required due to the subsite's close proximity to an industrial/residential area. The extracted air stream was to be treated by vapor phase GAC adsorption at a facility adjacent to the vapor extraction system or at the contaminated ground water treatment facility. In conjunction with the SVE, limited soil excavation and onsite incineration was to occur (HTI 2004). Figure 5-2, below, depicts the SVE extraction well and blower technology typically used at the subsite.

In January 1992, a PRP agreed to design a full-scale SVE system. This SVE system was installed in 1997. It attained remediation goals in May 2000, and entered into the "SVE-plus" phase, which required the system to perform for an additional two year period, until May 2002. The SVE remediation system was ultimately decommissioned and restoration activities completed in December 2003. During its operational period, the SVE system removed a calculated estimate of 422 pounds of EDB (USEPA 2007b; USEPA 2012b).

Figure 5-2. SVE Well and Blower Diagram



(Source: HTI 2004)

Well D and Primary Containment

In 1993, it was proposed that the plume be contained through groundwater extraction. More specifically, it was proposed that water be pumped from a newly installed remediation well for use in a nearby cooling tower that would serve as an air stripper for the contaminated groundwater (SSPAI 2013). A 1995 Engineering Evaluation/Cost Analysis (EE/CA) laid out various interim remedial alternatives, from which EPA selected a ground water removal action of pumping ground water and using the water at the facility as cooling water and stripping VOCs as the water is circulated to the cooling towers (USEPA 2005, USEPA 2007b). The Settling Defendant entered into an Administrative Order on Consent (AOC) in 1996, which required the party to implement this selected ground water removal action (USEPA 2005; SSPAI 2013). As a result, Well D went into operation in mid-1997 as the subsite interim remedy and has been pumping continuously ever since (Gresham 2011a; SSPAI 2008).

Well D is located within the groundwater contamination plume of the subsite and the North Landfill. It is 223 feet deep and is screened in two intervals from 142 to 162 feet bgs and 188 to 217 feet bgs. Normal discharge is in the range of 400 to 500 gpm, for a total of more than 200 million gallons per year (SSPAI 2008; Gresham 2010; USEPA 2007b).

In December 2002, a report was prepared showing groundwater data collected over the last five years on the performance of Well D. Based on the data submitted, EPA determined that the cleanup goals for the removal action were not going to be reached within a reasonable period of time, and that removal actions at the subsite had not removed all of the contamination (USEPA 2005).

Other Containment and Pumping

A secondary containment zone was created by the pumping of industrial wells IN-11 and IN-05, located at the Chief Ethanol plant. Some of the pumped water is treated through reverse osmosis and used for boiler water and cooling water. The untreated portion of the water is used as cooling water, as well as for process water for ethanol production, cleaning, washdowns, and maintenance. After the ethanol is created, the remaining corn mash, which is a by-product, is decanted and sold as livestock feed. The decanted water is evaporated to concentrate solids to be sold as syrup. The water vapor is condensed to create condensate that is recycled back to the process or treated in the waste water treatment system. Cooling tower blowdown and process water from equipment, cleaning, washdowns, and maintenance are treated on-site. Any VOCs pumped from the ground water would be volatilized by this entire process. All process treated waste water, reverse osmosis blowdown, and boiler blowdown is discharged to the West Fork of the Big Blue River (USEPA 2007b).

A tertiary containment zone was created from the pumping of Whelan Energy Center (WEC) wells A, B, and C. The water pumped from these wells is used at the WEC as non-contact cooling water and in other industrial processes (USEPA 2007b).

A 2008 Remedial Design Work Plan states that EDB has also been removed by seasonal irrigation wells such as I-49 and I-51 that intercept the plume (SSPAI 2008). The report does not mention pre-treatment of the water before irrigation usage.

Remediation Alternatives

In 2005, an Administrative Order on Consent (AOC) was issued that focused on the preparation of an FS for a final subsite action addressing groundwater contamination at the subsite (USEPA 2005). This was followed by a ROD in 2007, RAOs in 2008, and Consent Decree in 2008 (Gresham 2012c; SSPAI 2008; USDCDN 2008).

The 2008 RAO for groundwater at the subsite was to attain MCLs for EDB and CT in a defined area comprised of the zone where current and historical water-quality data establish the presence of EDB and CT above MCLs. The MCLs for CT and EDB are 5.0 µg/L and 0.05 µg/L, respectively (SSPAI 2008).

Various remedial alternatives were examined to meet the RAO, including the following:

- Alternative 1: No Action;
- Alternative 2: Ground water extraction at Well D, treatment and disposal at industrial facility;
- Alternative 3: Ground water extraction at Well D and at well near Source Zone, treatment and disposal at industrial facility;
- Alternative 4: Ground water extraction at Well D, treatment and disposal at industrial facility with alternative cleanup standard; and

- Alternative 5: Ground water extraction at Well D and enhanced in-situ bioremediation in the source area (USEPA 2007a; USEPA 2007b).

Alternative 5 was ultimately selected, because it offered what was deemed excellent short- and long-term protection, as well as reduction of mobility, toxicity, and volume through treatment. The estimated time to achieve this alternative was 45 to 50 years, which included 20 years of O&M (USEPA 2007a; USEPA 2007b).

Elements of alternative 5 (“the final remedy”) included:

- Groundwater capture via Well D (primary capture zone), WEC Wells A, B, and C, and IN-05 and IN-11 at the Chief Ethanol plant (secondary and tertiary capture zones);
- Source area treatment via enhanced bioremediation;
- Installation of new monitoring wells, with sampling via direct-push methods; and
- Continued monitoring of contaminants in groundwater.

(USEPA 2007a; USEPA 2007b).

Groundwater Capture

The groundwater capture element of the final remedy is a continuation of the interim remedy, consisting of the continued operation of ground water extraction wells, including Well D, WEC Wells A, B, and C, and Chief Ethanol Wells IN-05 and IN-11. The captured water was pumped to an existing cooling tower that was used to air strip the contaminants from the extracted groundwater, which was used as cooling water for industrial processes at the facility. This was to help contain the contaminated ground water plume and ensure that contamination levels are reduced to performance standards (SSPAI 2008).

Source Area Enhanced Bioremediation

The objective of source area enhanced bioremediation (SAEB) (also referred to as bioaugmentation or biostimulation) is to accelerate the degradation of CT and EDB by the addition of an electron donor substrate in the target zone to enhance microbial activity (SSPAI 2010). More specifically, it was determined that a carbon substrate amendment would be added to the source area in order to alter the groundwater geochemical environment to enhance reductive dehalogenation of CT and EDB (SSPAI 2008).

It is believed that both CT and EDB are readily degraded under anaerobic conditions by a variety of pure and mixed cultures from soil, sediment, and aquifers. EDB and CT are most amenable to biodegradation under anaerobic conditions (DO less than approximately 1 mg/L) that range from de-nitrifying to methanogenic (SSPAI 2010). It is further thought that microorganisms common to many aquifers are capable of reductive dehalogenation of CT and EDB under redox conditions that could be attained in the source area (Cohen 2009a).

A Treatability Study was conducted in 2009 to evaluate the potential for SAEB at the subsite and to determine whether it would be amenable to enhanced biodegradation. The Treatability study ultimately indicated that the aquifer characteristics were favorable for enhanced bioremediation because the aquifer was relatively homogenous, transmissivity was fairly high, and the groundwater gradient low. Furthermore, the redox conditions at the subsite were identified as mildly aerobic to de-nitrifying, which could be modified through substrate addition (SSPAI 2012b; Cohen 2009a).

Based on the results of the Treatability Study, an overall bioremediation plan was prepared. According to this plan, there was to be:

- Application of substrate to the source area through temporary injection points;
- Sampling of MW-8 for baseline redox results and contaminant concentrations; and
- Monitoring of downgradient results from existing wells (SSPAI 2010).

The substrate chosen was a commercially marketed vegetable oil emulsion, specifically Newman Zone Emulsified Vegetable Oil (EVO), a soybean-based vegetable oil emulsion. This was determined to be most appropriate for the site because it was a water-based emulsion with droplet size less than 1 micron, which can achieve rapid distribution through advection, dispersion, and diffusion in the aquifer. Oil in the emulsion could absorb to soil surfaces without significantly decreasing water flow through the soil, creating a long-lasting treatment zone. Formulation 190-6722 of the substrate was selected since its lecithin surfactant would likely be the most strongly retained in the sandy soil of the aquifer. The emulsion's physical characteristics, buoyancy and partitioning, were thought to make it effective in targeting contaminants in the upper portion of the aquifer. All ingredients of the substrate are non-toxic and food grade. The effects of the emulsion were expected to last two to five years (SSPAI 2010).

Concentration data implied that the contamination occurs in a very thin (less than one foot) interval at the water table. To produce a conservative substrate volume estimate, however, the treatment zone was assumed to be 5 feet thick. After weighing in various other factors, it was determined that 49 pounds of vegetable oil, or 107 pounds of the Newman Zone Vegetable Oil Emulsion, were required to meet the stoichiometric hydrogen demand. Since the seepage velocity at the source area is relatively high (400 feet/year), there could be a rapid flushing through the system. As a result, the mass of vegetable oil was multiplied by a safety factor of 10, for a total of 1,070 pounds, or about 133 gallons of emulsion. In order to maximize the radius of influence (ROI) at each injection location, the emulsion was to be diluted in mixing tanks immediately prior to injection. This would yield a total injected volume of about 1,500 to 3,000 gallons of diluted emulsion. The impact of substrate injection on subsurface conditions was anticipated to last for a period of up to five years, and so only a single injection was planned (SSPAI 2010). Injection of the substrate amendment solution was to be performed upgradient of MW-08, in the source area for CT and EDB contamination (SSPAI 2008). In order to evaluate the effectiveness of treatment, monitoring of redox conditions was to be performed downgradient at MW-8 and MQ-01 (Cohen 2009a; SSPAI 2008).

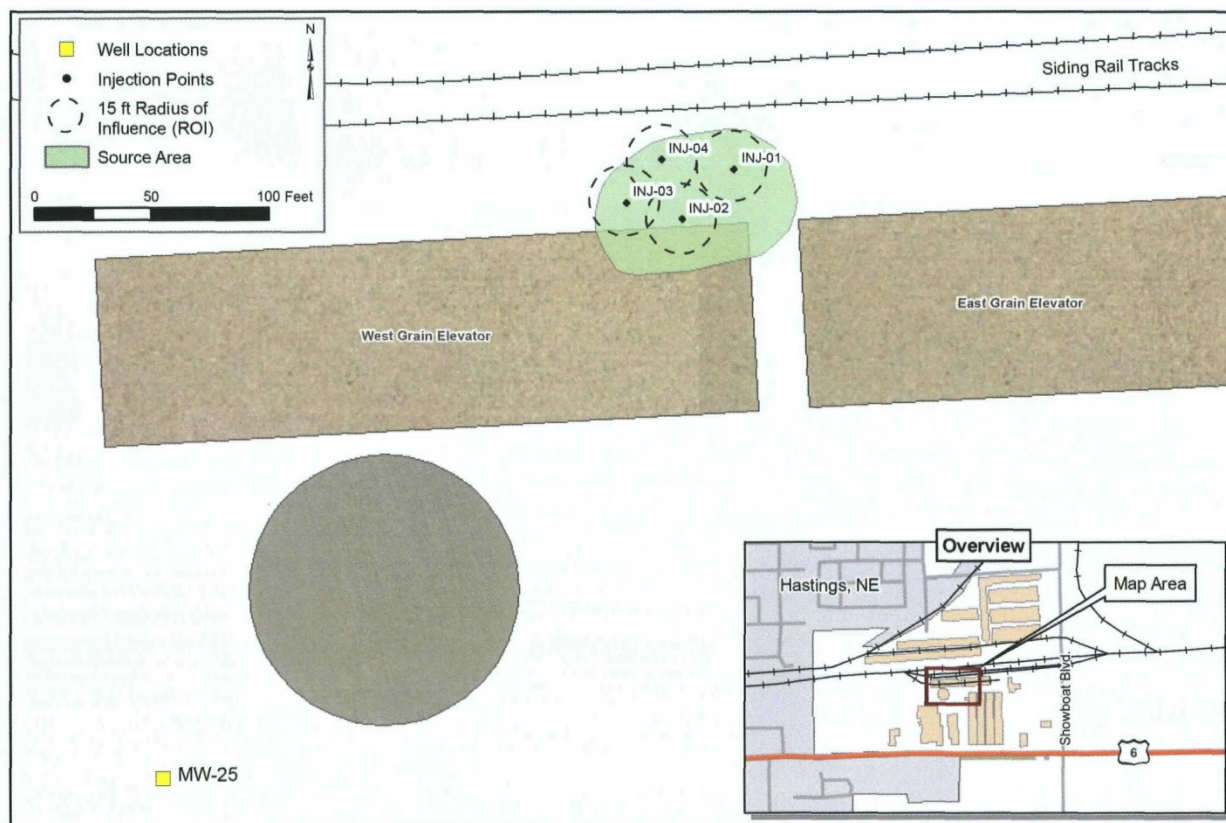
The SAEB was completed in July 2010. Approximately 1,080 pounds (135 gallons) of Newman Zone EVO formulation 190-6722 was injected at the water table, in the shallowest saturated portion of the aquifer. Prior to injection, the emulsion was diluted with potable water at a ratio of 15 to 20 parts water to one part emulsion. Sodium bicarbonate (0.1% solution) was added to the diluted substrate to compensate for slightly acidic conditions caused by the North Landfill and to prevent a short-term drop in pH (Gresham 2011a; Gresham 2010; SSPAI 2010a).

The estimated ROI at each injection location was about 15 to 20 feet. Substrate was injected through four temporary, uncased Geoprobe[®] borings evenly spaced about 30 feet apart across the source area to ensure that it was covered with ROI overlap. Substrate was injected over a two-foot perforated interval at the bottom of each boring. A total of 525 to 600 gallons of diluted emulsion was injected at each location, yielding a total injected volume of 2,250 gallons. A Geoprobe[®] 7720DT direct push technology (DPT) rig was used to drive each boring to its total depth at or slightly above the water table, at approximately 125 to 130 feet bgs. Injection depth varied from 117 to 124 feet bgs to ensure that the emulsion reached the soil immediately above and at the water table. The average pumping rate was 4 to 5 gpm. Injection pressure was maintained at less than 1 pound per square foot (psi)/foot borehole depth (at or about 120 psi). Upon completion of injection, each boring was filled with bentonite chips and hydrated for effective abandonment (Gresham 2010; SSPAI 2010a). Figure 5-3 depicts the injection locations.

Installation of New Monitoring Wells

Monitoring well installation activities were to occur as part of the remedial design plans, including installation of direct push probes at several locations. One pair of nested monitoring wells (shallow and deep) were to be installed south of the WEC, while a second pair of nested monitoring wells (intermediate and deep) were to be installed east of the WEC. Direct push sampling in the immediate vicinity of each well pair was set to occur in order to determine the best depths at which the monitoring wells would be screened (SSPAI 2008).

Figure 5-3. Emulsified Vegetable Oil Injection Locations



(Source: Gresham 2010)

The direct-push investigation was completed in May 2009. Five borings were pushed to depths ranging from 202 to 212 feet bgs. During this investigation, VOC concentrations in groundwater were measured using depth-discrete sampling. Samples were taken every ten feet between the total depth of each boring and the depth of the water table (Gresham 2010).

New monitoring well installation was completed in October 2009. Two nested pairs of monitoring wells were installed (MQ-10, MQ-11, MQ-12, and MQ-13). Well pair MQ-10/MQ-11 has screens that are 10 feet long set at intermediate and deep intervals (150.8 to 160.8 feet bgs, and 190 to 200 feet bgs). Well pair MQ-12/MQ-13 has screens that are 10 feet long and set to shallow and deep intervals (143 to 153 feet bgs and 180 to 190 feet bgs) (Gresham 2010; SSPAI 2009).

Groundwater Monitoring

No significant changes were made to sampling or analytical methodologies (SSPAI 2008). Groundwater is sampled for VOCs including EDB and CT using method EPA 524.2, which has a method detection limit (MDL) adequate to quantify concentrations below the MCL (Gresham 2010; SSPAI 2008). The primary analytical method has been gas

chromatograph/mass spectrometer (SSPAI 2008). Depending on the well, monitoring is performed either quarterly, semi-annually, or annually (SSPAI 2008; Borovich 2011a).

5.3.1 EFFECTIVENESS OF REMEDIATION TECHNOLOGIES

A calculated estimate of 354 pounds of EDB were removed from soils as a result of the SVE pilot test conducted in 1990, and over 400 pounds of EDB was estimated to have been removed from the source area as a result of SVE efforts conducted between 1997 and 2002 (USEPA 2007b; Gresham 2011a). The sections below detail the effectiveness of remediation efforts at Well D, other wells, and bioremediation.

Well D

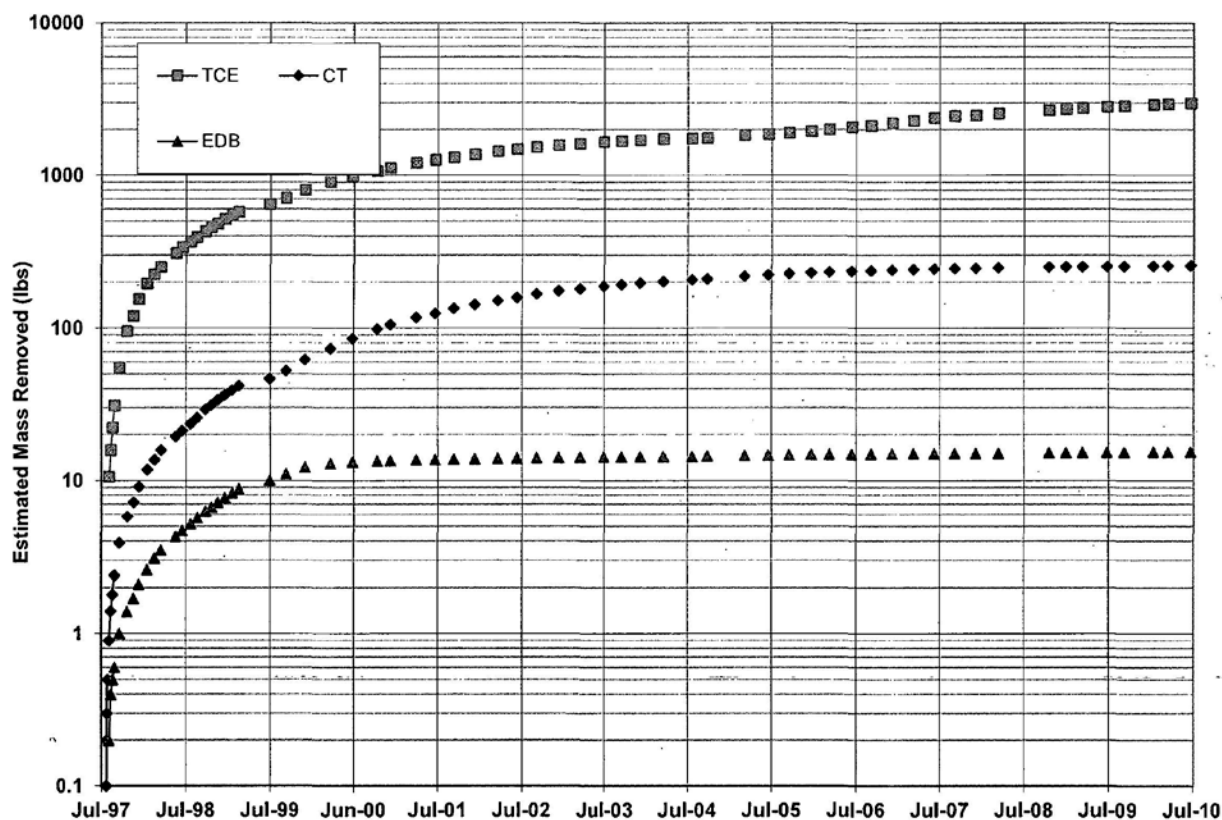
By 2002, the EDB plume downgradient of the source area had diminished. Concentrations in the well had decreased from highs of approximately 5 µg/L in 1997, when the well was first put into operation, to lows of 0.15 µg/L during its fifth year of operation. Data showed that while some elevated EDB concentrations still occurred in the source area, concentrations were significantly lower in the downgradient wells (HTI 2002). Mass removal of target compounds was considered to have met or exceeded expectations because 80% of the estimated EDB in the groundwater plume was removed. For more than two years, the cumulative EDB removal curve remained flat, indicating only very minor amounts of EDB being intercepted at Well D. In addition, it was believed that natural attenuation had drastically reduced EDB concentrations downgradient from the source area to levels at or approaching the MCL. However, despite these results, EPA determined that removal actions at the subsite had not removed all of the contamination, and that the cleanup goals for the removal action were not going to be reached within a reasonable period of time. As a result, in 2005 an AOC was issued that focused on the preparation of an FS for a final subsite action addressing groundwater contamination at the subsite (USEPA 2005; HTI 2002).

As of 2008, Well D had removed more than an estimated 15 pounds of EDB (SSPAI 2008). In 2009, it was reported that concentrations of EDB at Well D had decreased to historic lows that did not exceed 0.1 µg/L in the prior six sampling rounds. This change in the EDB concentration reflected a depletion of EDB released from the source area west of well MW-08. In effect, the data indicated that releases of EDB from the source area had been reduced by 99 percent or more. Regardless of this finding, in 2009, the Nebraska Department of Environmental Quality conveyed that it did not feel that Well D, along with the other extraction wells in use, were sufficient to prevent the contaminant plume from migrating to the southeast (Cohen 2009b).

Samples collected from Well D from around 2007 through 2011 showed that EDB was occurring at levels slightly above the MCL of 0.05µg/L (Asher 2011). In addition, concentration data from Well D as of 2011 indicated that the current mass of EDB in groundwater west of Well D was equal to approximately 1.4 pounds. This was a reduction from the 3.4 pounds estimated to be present in 2001. Well D was thought to be extracting about 0.1 pounds of EDB per year. This did not represent the current EDB flux from the source, but rather the mass flux that left the source area some years ago. It was thought that the impact of the reduction in flux from the 1997 through 2002 remediation efforts had not yet reached Well D. Based on calculations of

groundwater velocities, it was expected to reach Well D in the near future, at which point EDB concentrations would decline significantly from their 2011 concentrations of approximately 0.1 µg/L (Gresham 2011a). Figure 5-4 depicts the amount of EDB removed from Well D between 1997 and 2010.

Figure 5-4. Amount of EDB Removed from Well, 1997 - 2010



(Source: Gresham 2011a)

As a result of the continuous pumping of Well D, by 2011, the two groundwater plumes had been split into eastern and western portions. The western portion was captured by Well D, while the eastern portion was captured by the WEC wells and intervening irrigation wells. Recently installed monitoring wells, MQ-10 through MQ-14, confirmed that subsite contaminants were being contained, as concentrations of COCs above the MCLs have not been observed (Gresham 2010).

Around this time, some felt that Well D had reached a point where it was no longer useful in reducing EDB concentrations in groundwater downgradient from the subsite with respect to the reduction of the EDB and CT mass entrained in the aquifer west of Well D. During prior sampling intervals, Well D had been extracting only small amounts of EDB, mostly from non-subsite sources. This was in comparison to the larger residual mass of EDB estimated to be present east of Well D. In addition, EDB concentrations at Well D were nearing MCLs (Gresham 2012c; Gresham 2011a). Finally, some believed that continued operation of Well D

would actually inhibit migration of EDB to the east of Well D rather than capturing it. Termination of operation of Well D could encourage the migration of subsite COCs to their ultimate capture and removal from the aquifer by WEC wells A, B, C, E and F. Furthermore, some residual mass of contaminants not captured by Well D was being entrained and inhibited from migrating with groundwater. If pumping from Well D was eliminated, contaminated groundwater in these areas would migrate more readily toward ultimate removal points in the WEC wells (Gresham 2011a).

As of February 2012, EPA agreed that Well D had become more effective at extracting groundwater contamination related to other Hasting subsites. EPA also agreed that concentrations of EDB were nearing the MCLs at Well D (Gresham 2012a). Finally, it was understood that the effectiveness of Well D in removing TCE prevented the termination of its operation (Gresham 2012c; Gresham 2011a). To view plume maps over time, from 1997 through 2002, please see Appendix C, Maps 2A-F, and in 2010, Appendix C, Map 3 (as of 2010).

Other Wells

Between 2005 through 2009, concentrations of EDB in well MW-08 declined by orders of magnitude independent of the seasonal cycle. Since June of 2006, the concentration of EDB in well MW-08 has not exceeded 2.3 µg/L. This is about two orders of magnitude lower than the maximum concentrations measured in 2004, although still almost two orders of magnitude greater than the MCL of 0.05 µg/L. This change in the EDB concentration is attributed to a depletion of EDB released from the source area west of well MW-08 (SSPAI 2010).

As of 2012, data from the effluent from the Chief Ethanol extraction and treatment wells, wells IN-5 and IN-11, and the extraction and treatment wells at the WEC show that for many more than four consecutive monitoring periods, the effluent water quality at these two locations has demonstrated EDB and CT at non-detectible concentrations or concentrations below the MCLs. Periodic sampling of wells IN- 5 and IN-11 have established that the portion of the EDB and CT plume originating from the subsite and captured by these wells has been fully and completely remediated. These results demonstrate that the wells continue to be effective in containing, extracting and treating EDB and CT entrained in groundwater (Gresham 2012c).

EDB and CT are also being removed by seasonal irrigation wells, such as 1-49 and 1-51, which intercept the plume. Sampling data from the irrigation wells indicate that the plume of CT and EDB is diminishing in size and that the overall concentrations of EDB and CT are decreasing. These data must be viewed in light of the fact that irrigation wells pump at a high rate, allowing volatilization to occur, and if there were monitoring wells in the same general area, the concentrations of the COCs in the ground water measured from those monitoring wells would likely appear higher (Cohen 2009b).

Bioremediation

Although monitoring of CT and EDB concentrations is ongoing, there have not yet been any definitive impacts of the SAEB treatment on downgradient EDB or CT concentrations. The

groundwater flow rate from the source area treatment to well MW-08 is approximately two years. Consequently, the impacts from the 2010 treatment have not yet been seen. Furthermore, it is possible that the shallowest portion of the aquifer is somewhat finer grained and therefore of a lower transport velocity than the aquifer as a whole. If this were to be the case, the impacts from the 2010 treatment may take even longer than 2 years to be observed in well MW-08. However, it is believed that the bioremediation treatment will further reduce the remaining mass of contaminants and mass flux of EDB from the source area (Gresham 2011a).

General

Overall, EDB concentrations have been steadily decreasing at all locations. As of July 2012, hydraulic containment of the subsite's COC plumes had been achieved thanks to a combination of pumping Well D, the WEC wells, and Chief Ethanol wells IN-05 and IN-11. This has been enhanced by the recent expansion in capacity of the WEC and corresponding demand for additional cooling water in recent years (wells E and F). EPA has acknowledged that the various components of the 2007 ROD (extraction and treatment of contaminated groundwater; enhanced in-situ bioremediation at the contaminant source area; and groundwater monitoring) have been effective in reducing the extent and concentration of COCs at the subsite, including of EDB. Furthermore, EPA has acknowledged that capture of the outer reaches of the subsite plume has been achieved. The continued decline in concentration and mass of CT and EDB is what would be expected from a dying contaminant source for which there is no mechanism to replace the mass carried away by groundwater. However, as of 2012, COCs were still present in the plume above their respective MCLs (Gresham 2012c; Gresham 2012d).

5.3.2 COSTS OF REMEDIATION TECHNOLOGIES (IF AVAILABLE)

Only cost estimates and actuals in relation to the RAO activities are currently available. As the data below shows, estimated capital costs for groundwater monitoring and extraction at Well D were minimal since the system was already operating. On the other hand, the annual O&M costs for the extraction remedy were estimated to be more than \$90,000 per year. The actual costs reported for approximately two years of operation, from 2007 through 2009, total nearly \$140,000 when EPA oversight is added in, which is lower per year than estimated. Note that time spent evaluating the quarterly monitoring data has not been included, or else costs would be higher. No costs were originally estimated for the installation of new monitoring wells; however, various wells were installed, with a total actual cost of around \$150,000. Actual costs for the SAEB remedy on were less than half the amounts estimated, which can be attributed to an efficient design and problem-free implementation. For instance, the field schedule was completed in two days instead of the anticipated four days. O&M costs associated with the SAEB remedy have not yet been obtained (Gresham 2010). An additional breakdown of the cost estimates for the SAEB remedy is included in Table 5-2.

5.3.3 CLEAN UP STATUS/RESULTS

According to an AOC dated February 14, 2012, EPA recommended that the Settling Defendant implement measures to facilitate more rapid degradation of subsite-related groundwater contamination in the portion of the subsite closer to the source. The EPA further indicated that *in situ* chemical oxidation could be one option that the Settling Defendant may want to consider (Gresham 2012a). It is unknown if any such measures were indeed implemented.

Activities related to the 2008 RAOs are still occurring today. As of May 2012, EPA indicated that the Settling Defendant could cease sampling for EDB at eight locations (Gresham 2012b). In July 2012, the Settling Defendant requested to terminate its monitoring and groundwater extraction requirements pursuant to performance standards. EPA did not consent to this request.

Table 5-1. Estimated and Actual Costs of Remediation Activities

	Groundwater Monitoring and Extraction at Well D	Installation of New Monitoring Wells	SAEB
Estimated Costs from 2007 FS and ROD			
Capital Costs	\$1,000	N/A	\$105,360
Annual O&M	\$91,344	N/A	\$43,249
Actual Costs (Estimated from Project Billing)			
Capital Costs	\$0	\$89,382	\$46,053
O&M to Date	\$118,172	N/A	N/A
USEPA Oversight Costs	\$20,000	\$60,405	N/A

(Source: Gresham 2010a)

FS – feasibility study

N/A – not applicable

O&M – operation and maintenance

ROD – record of decision

SAEB – Source Area Enhanced Biodegradation

Table 5-2. Breakdown of Cost Estimates for the SAEB Remedy

Cost Estimate for Selected Remedy				
Item	Unit	Unit Quantity	Unit Cost (\$)	Total Cost (\$)
Capital Costs				
Treatment Equipment	LS	1	\$40,000	\$40,000
Design & Construction O/S	LS	1	\$47,800	\$47,800
			Subtotal	\$87,800
Other Costs				
Project Management (5%)			4,390	4,390
Contingency (15% of Subtotal)			13,170	13,170
Total				\$105,360
O&M				
Annual Costs	LS	1	\$135,593	\$135,593
20-Year O&M (Present Value)	LS	1	\$1,091,798	\$1,091,798
Total 20-Year Costs (Capital + O&M P.V.)	LS	1	\$1,197,158	\$1,197,158

(Source: USEPA 2007b)
LS – lump sum
O&M – operation and maintenance
PV – present value
\$ - U.S. dollars

However, EPA did further reduce the number of wells and sampling frequency required. In addition, EPA provided a framework by which the Settling Defendant can attain performance standards in the vicinity of Well D, which would result in the Defendant's no longer being obligated under the Consent Decree to pay for the operation of Well D (Gresham 2012d).

5.3.4 PROBLEMS ENCOUNTERED

According to an AOC dated February 14, 2012, EDB concentrations were nearing MCLs and therefore EPA foresaw a time at which it would be appropriate to release the Settling Defendants from their requirements related to the operation of Well D. As a result, EPA modified prior sampling requirements. New sampling requirements indicated that when four consecutive quarterly groundwater samples collected from Well D indicate results below the MCL for EDB, the EPA will agree that the Settling Defendants have achieved the Performance Standards for EDB at Well D. However, if EDB concentrations rebound above the MCL before the four consecutive quarterly samples are collected, then the countdown will be terminated but may be recommence when EDB concentrations fall back below the MCL. This sampling requirement change is only in relation to Well D; it does not impact other performance standards for subsite-related COCs throughout the remainder of the subsite (Gresham 2012a).

There are various factors influencing remediation effectiveness or the ability to measure such effectiveness. First, there are fluctuating concentrations of EDB historically observed in

MW-08, which is located about 800 feet downgradient from the source area. This is the result of the thin layer of contaminated groundwater emanating from the source area. When groundwater levels would rise, this thin layer moved above the screened interval in the well and so sample concentrations from the well would decline significantly (Gresham 2011a). Second, it has been difficult to measure the success of recent efforts, as there is a lack of monitoring wells to the east. The source area treatment is far enough away from the next downgradient monitoring well that it takes a while to get any groundwater impacted by treatment from the source area to the monitoring well (Borovich 2011b; Gresham 2013).

6.0 RESEARCH FINDINGS AND CONCLUSIONS

The remediation systems at the four sites with EDB contamination in soils and groundwater include (1) groundwater extraction and treatment for the four EDB-contaminated plumes at MMR; (2) AS/SVE at the Home Oil site; (3) groundwater extraction and treatment for hydraulic control of the perched aquifer in conjunction with SVE and groundwater extraction and treatment with MNA of the basal aquifer at the Del Monte; and (4) SVE of soils with groundwater extraction and treatment at the Hastings OU6 site. The general remediation system design considerations and constraints are reviewed for each of these remediation systems to understand the primary selection criteria used during the remediation alternative selection process. The findings from the site characterization and from the remediation evaluation and selection, construction, O&M, and long-term monitoring are summarized and compared to illustrate how lessons can be learned notwithstanding rigorous evaluation of the general remediation system design considerations and constraints. Table 6-1 summarizes the remediation systems at the four sites.

Table 6-1. Summary of Remediation Systems Evaluated

	Fuel Source		Pesticide Source	
	MMR	Home Oil	Del Monte	Hastings OU6
Extraction, Treatment, and Re-injection	✓		✓	✓
GAC Treatment	✓		✓	
<i>Ex-Situ</i> Phytoremediation			✓	
Air Stripping			✓	✓
Air Sparge	✓	✓		
SVE	✓	✓	✓	✓
Catalytic Oxidation	✓			
GAC	✓			✓
Bioaugmentation				✓
Wellhead Protection	✓	✓	✓	
MNA			✓	
Source Excavation & Impermeable Cap			✓	
Institutional Controls (Risk Management)	✓		✓	

GAC – Granular activated carbon
MMR – Massachusetts Military Reservation
SVE – soil-vapor extraction

OU – Operable Unit
MNA – monitored natural attenuation

6.1 GENERAL DESIGN CONSIDERATIONS AND CONSTRAINTS FOR EVALUATED REMEDIATION SYSTEMS

A brief overview of design elements that must be evaluated is presented to illustrate general considerations and constraints of each remediation system for a particular site with its unique site characteristics. No remediation system is optimal for all conditions and each system has benefits and detriments that must be balanced in the evaluation process. A general understanding of the remediation systems and their components can help understanding of the limitations and need for mitigation and augmentation. For instance, groundwater extraction, treatment, and re-injection can modify groundwater flow parameters requiring system optimization to maintain effectiveness and hydraulic control.

Below is a brief overview of the different remediation technologies potentially applicable for remediation of EDB that were selected for implementation at each of the four selected sites. The selection process for the remediation alternative at each site presumably included a rigorous evaluation to determine suitability for the individual site conditions. Each technology is introduced below, including how it conceptually works and some of its basic parameters. Table 6-2 summarizes some of the basic considerations, limitations, and requirements for each remedial technology. The remediation selection process is more extensive and detailed.

6.1.1 AIR SPARGING

Air Sparging is an *in situ* remedial technology that reduces concentrations of volatile constituents in petroleum products that are adsorbed to soils and dissolved in groundwater. This technology, which is also known as “*in situ* air stripping” and “*in situ* volatilization” involves the injection of contaminant-free air into the aquifer, enabling a phase transfer of hydrocarbons from a dissolved state to a vapor phase. The air is then vented through the unsaturated zone. General information about air sparging technology is included in Appendix D.

Air sparging is most often used together with SVE in which the volatiles in the soil gas are evacuated, but it can also be used with other remedial technologies. When AS is combined with SVE, the SVE system creates a negative pressure in the unsaturated zone through a series of extraction wells to control the soil gas plume migration (note that SVE also creates a vacuum to strip volatiles adsorbed to soils in the vadose zone). General information about SVE technology is included in Appendix E. This combine system is called AS/SVE.

AS is generally more applicable to the lighter and more volatile gasoline constituents (e.g., EDB, BTEX) because they readily transfer from the dissolved to the gaseous phase. AS is less applicable to diesel fuel and kerosene. Air sparging requires appropriate aquifer and contaminant distribution characteristics to be most effective, such as higher permeability and hydraulic conductivity to increase the ROI (i.e., the treatment zone for the air injection well), a moderate and steady groundwater flow, and a well characterized and concentrated contaminant plume so that the injection wells can be located to be most effective. AS forces air into the aquifer that eventually escapes with the entrained volatiles to the atmosphere, so contaminated air can intrude into surrounding buildings and the atmosphere requiring other mitigation such as an SVE system to extract and treat the soil gas. The injection wells, airlines, pumps, and other equipment necessary require access, so structures and other operations can interfere.

6.1.2 SOIL VAPOR EXTRACTION

SVE, also known as soil venting or vacuum extraction, is an *in situ* remedial technology that reduces concentrations of volatile compounds adsorbed to soils in the unsaturated (vadose) zone. A vacuum is applied to the soil matrix to create a negative pressure to strip volatiles adsorbed to soil or trapped in the soil pore space and also creates a pressure gradient causing movement of contaminated soil gas toward extraction wells. Volatile constituents with a relatively higher vapor pressure, such as EDB, are readily removed from the subsurface through soil vapor extraction wells. The extracted vapors are then treated, as necessary, and discharged to the atmosphere or reinjected to the subsurface, such as into air sparging injection wells. General information about SVE technology is included in Appendix E.

This technology has been proven effective in reducing concentration of VOCs and certain semi-volatile organic compounds (SVOCs) found in petroleum products and other products, such as solvents. SVE is generally more successful when applied to the lighter more volatile petroleum products such as gasoline. Diesel fuel, heating oils, and kerosene, which contain a higher proportion of less volatile compounds, are not readily treated by SVE; however, the volatile fraction of compounds in these petroleum products are still effectively treated by SVE. Consequently, heavier petroleum products with volatile additives, such as EDB, can still be effectively treated using SVE to remove those volatile constituents. Each of the four sites evaluated in Sections 2 through 5 of this report successfully used SVE as part of its remediation design to treat EDB.

SVE requires moderately to larger grained soils to increase the ROI. But SVE works poorly in shallow soils, such as if an aquifer is within approximately 20 feet of ground surface, because of short-circuiting (i.e., direct communication with the atmosphere between the vacuum created at the extraction well screened interval and the surface); a low permeability surface at ground level over the treatment zone, such as a parking lot or a building foundation, can help to increase the ROI. Air treatment of the SVE effluent is necessary, which requires permitting.

6.1.3 BIOAUGMENTATION/BIOSTIMULATION – REDUCTIVE DEHALOGENATION

Reductive dehalogenation involves the removal of a halogen substituent from a molecule with concurrent addition of electron to the molecule. Reductive dehalogenation is an important means of biodegradation of numerous compounds, including EDB as well as chlorinated solvents (e.g., PCE and TCE), organochlorines pesticides, alkyl solvents, and aryl halides. Reductive dehalogenation is the only known biodegradation mechanism for certain significant pollutants including halogenated aromatics. It most readily occurs in anaerobic conditions. General information about reductive dehalogenation technology is included in Appendix F.

Reductive dehalogenation occurs in most groundwater with existing microbes, but microbes specifically grown to biodegrade target compounds can be injected to foster augmented degradation rates (i.e., bioaugmentation/biostimulation). Additionally, other substrates necessary for optimal growth of the microbes, which degrade the target contaminants as they thrive, can also be injected, such as EVO (note that residual petroleum hydrocarbons dissolved in groundwater from a source can often provide the electron donor for reductive dehalogenation rather than injecting another carbon substrate amendment, such as EVO). Injection of substrates

for bioaugmentation requires characterization of the aquifer geochemistry, contaminant concentrations, microbial counts, etc. to determine the appropriate amounts required. Low concentrations of dissolved oxygen, typically less than 1 mg/L, and appropriate reduction/oxidation (redox) potential indicating reducing are necessary for optimal anaerobic conditions for reductive dehalogenation; injection of appropriate substrates can also improve geochemical conditions for reductive dehalogenation. Appropriate commercially available substrates, such as EVO, must be selected to provide optimal dispersion increasing the ROI while minimizing negative impacts on groundwater flow in the aquifer.

6.1.4 GROUNDWATER EXTRACTION AND TREATMENT

Groundwater ETD (or EDR), which is commonly referred to as pump and treat, is one of the most widely used groundwater remediation technologies and has a long history. Conventional groundwater extraction and treatment methods involve pumping contaminated water to the surface for treatment. Variations and enhancements of conventional groundwater extraction and treatment include hydraulic fracturing as well as chemical and biological enhancements for the treatment of recovered contaminated groundwater. The general failure of the groundwater ETD/ETR approach was identified as its inability to achieve restoration (i.e., reduction of contaminants to levels required by risk-based criteria) within ten years, as anticipated in the design phase of many projects. Combining the groundwater ETD/ETR approach with *in situ* bioremediation provides further opportunities for improving the effectiveness of groundwater cleanup. Groundwater extraction and treatment systems are used primarily to accomplish hydraulic containment and treatment. Extraction of groundwater causes a depression in the potentiometric surface of the aquifer as groundwater elevations diminish such that hydraulic containment is achieved by general reversal of the local groundwater flow near the extraction well. General information about ETD/ETR technology is included in Appendix G.

Groundwater ETD/ETR systems require a well characterized site, including a good understanding of contaminant distribution and movement as well as a good understanding of groundwater flow. Specific aquifer and contaminant distribution is necessary to optimize contaminant recovery and ensure protection of downgradient receptors. Groundwater extraction typically requires pumping a large volume of water for many years, so the energy costs can be high particularly when the groundwater is deep (i.e., costs increase substantially with the depth of groundwater).

6.1.5 MONITORED NATURAL ATTENUATION

Natural attenuation is the reliance on inherent processes within the context of a carefully controlled and monitored site cleanup approach to achieve site-specific RAOs within a time frame that is reasonable compared to that offered by other more active methods. The inherent natural attenuation processes that are at work in such a remediation approach include a variety of physical, chemical, or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater. These *in situ* processes include biodegradation; dispersion; dilution; sorption; volatilization; radioactive decay; and chemical or biological stabilization,

transformation, or destruction of contaminants (USEPA 1999). General information about MNA technology is included in Appendix H.

MNA includes installation and development of groundwater monitoring wells and a program of sampling and data evaluation to determine progress of natural attenuation, statistical trending of contaminant concentrations, conditions for optimal natural attenuation, and the natural attenuation capacity of the plume within the aquifer. MNA as a selected remediation alternative typically requires contaminant concentrations nearing their remedial action objective (i.e., MCL or other risk-based criterion) and adequate historical data to predict trending of contaminant concentrations to be protective of HHE.

6.2 SITE IMPLEMENTATION OF EDB REMEDIATION SYSTEMS

One principle of remediation is to ensure that the source of the contamination is controlled or eliminated to avoid re-contaminating treated media. For instance, treating EDB contamination in groundwater will require excessive O&M durations if the source of the contamination continues to supply the contaminant rendering the groundwater treatment ineffective in the long-term. Elimination of the source of groundwater contamination remaining in the vadose zone may require physical removal of shallow and accessible sources, but deeper and otherwise inaccessible sources, such as those sources under structures that cannot be removed or avoided, may require treatment for source elimination or capping to control leaching from the source. Site specific conditions can limit effective alternatives for treatment and control of the source.

6.2.1 EXTRACTION, TREATMENT, AND DISCHARGE/RE-INJECTION

As indicated in Section 6.1, the principle of an ETD/ETR system is to remove the contaminated groundwater from the aquifer before reaching the receptors and then to use *ex situ* treatment systems to remove the EDB contamination from the water before being re-injected into the aquifer or otherwise discharged to surface waters. The interception and extraction of all contaminated groundwater is virtually impossible, but the objective of extraction systems is to optimize the placement and pumping rate of extraction wells to provide hydraulic control of the contaminant plume and intercept the highest concentrations in the plume. Re-injection of treated water is also planned to optimize hydraulic control and minimize residual contaminant concentrations at the receptor exposure point by mixing the treated (i.e., uncontaminated) water with any residual groundwater contamination that is not intercepted by the extraction system. Otherwise, extracted and treated groundwater can be used for other beneficial uses, such as for cooling water (see the Hastings Groundwater OU6 site, Section 5.0), irrigation, etc.

Multiple options are available for *ex situ* treatment of extracted contaminated groundwater depending on the principle contaminants. In the case of EDB, its low vapor (i.e., relatively high volatility) make air stripping an obvious choice, although air treatment may then be required to prevent release to the atmosphere. EDB, however, has a lower propensity to adsorb to organic carbon, which largely accounts for its mobility in groundwater. Consequently, GAC treatment of EDB-contaminated water often requires substantial surface area of the carbon to adequately capture EDB molecules and reduce concentrations to the MCL (0.05 µg/L for federal, but lower in some states, such as Massachusetts at 0.02 µg/L). Consequently, experimentation with other *ex situ* treatment, such as phytoremediation at the Del Monte site, has been successfully

attempted. Additional adsorptive treatment technologies other than GAC, such as polymeric resins adsorption that uses microwave energy for regeneration, may be applicable. Bench-scale and/or pilot testing could be performed to evaluate effectiveness prior to full-scale implementation.

Table 6-2. Summary of Remediation Technologies

	Air Sparging	SVE	Extraction and Treatment	Bioaugmentation – Reductive Dehalogenation
Target Media	• Soil and groundwater	• Soil	• Groundwater	• Groundwater
Hydrogeologic characteristics	• High hydraulic conductivity • Must not be located in a confined aquifer	• NA	• Moderate to high hydraulic conductivity • Well characterized groundwater flow	• High hydraulic conductivity for injections
Groundwater Plume Characteristics	• Well defined extent • Concentrated COPC extent	• NA	• Well defined extent • Concentrated COPC extent	• COPC at very high concentrations can be toxic to microbes
Geology Characteristics	• Large grained soils	• Large grained soils	• NA	• Large grained soils
Depth to treatment zone	• Generally NA	• At least 20 feet bgs (or requires an impermeable pad to increase the ROI)	• Shallow aquifers (higher cost for deep aquifers)	• NA
Most commonly used with	• SVE	• Air Sparging	• GAC for effluent treatment	• MNA
Most effective	• Volatile compounds	• Volatile compounds	• Compounds with less propensity to adsorb to aquifer media	• Halogenated organics
Not effective for	• Free Product Removal • Less volatile compounds (e.g., SVOCs)	• Metals and lesser volatile organics	• NA	• Metals (other biodegradation processes attenuate most organics)
Cost effective	• Low to moderate	• Low to moderate	• Higher	• Lower
Components that determine effectiveness	• Permeability • Vapor/dissolved phase partitioning	• Permeability • Volatility	• NA	• Permeability • Geochemistry (see next)

Table 6-2. Summary of Remediation Technologies

	Air Sparging	SVE	Extraction and Treatment	Bioaugmentation – Reductive Dehalogenation
Optimal Geochemistry Requirements	<ul style="list-style-type: none"> • NA 	<ul style="list-style-type: none"> • NA (only treats vadose zone soil) 	<ul style="list-style-type: none"> • NA 	<ul style="list-style-type: none"> • Anaerobic conditions (DO less than 1 mg/L) • Reducing conditions • Groundwater pH – 6 to 8 • Groundwater Temp – > 20°C
Potential Issues	<ul style="list-style-type: none"> • Stratified Soils • Changes to groundwater flow and migration of contaminated groundwater away from treatment area • Infusion of DO inhibiting anaerobic biodegradation • Vapor release (mitigated if used with SVE) 	<ul style="list-style-type: none"> • Air Permit Required • Short-circuiting to surface 	<ul style="list-style-type: none"> • Contaminant plume movement (both horizontal and vertical) • ROI • Freezing and thawing 	<ul style="list-style-type: none"> • Substrate injections may have limited radial influence • Substrate injections may alter groundwater flow • Delayed contaminant rebound after stimulation

bgs – below ground surface

DO – dissolved oxygen

mg/L – milligrams per liter

NA – Not applicable

SVE – soil vapor extraction

SVOC – semi-volatile organic compound

°C – degrees Celcius

COPC – contaminant of potential concern

GAC – granular activated carbon

MNA – monitored natural attenuation

ROI – radius of influence

6.2.1.1 Extraction and Re-Injection Systems

Three of the four sites evaluated, including MMR, Del Monte, and Hastings, have used extraction and treatment systems (see Table 6-1). All extraction and re-injection systems have been successfully constructed and operated to protect receptors, but each site has augmented these systems to some degree to optimize overall protection of human health and the environment. MMR used an AS/SVE system at one of the four plumes to treat the soil source of the groundwater contamination to reduce the leaching of further EDB into the groundwater and thereby both reduce the load on the groundwater extraction and treatment system and reduce the duration of the treatment. The Del Monte site capped the area of its soil source to reduce infiltration of surface waters and precipitation to minimize the leaching of EDB contamination from the soil to the groundwater. The Hastings site included SVE, bioaugmentation, and MNA to its treatment.

The design challenge of placing the extraction well screened interval in the appropriate locations and at the appropriate depths is demonstrated at plume FS-1 at MMR in which the higher concentrations of EDB-contaminated groundwater are found deep within the aquifer before rising abruptly and discharging to surface waters. The plume at FS-1 also demonstrates how EDB migrates at a different rate and potentially by a different flow path because the investigations at FS-1 found some fuel-related compounds (e.g., toluene) near the source but found EDB further downgradient. The plume at FS-12 also showed how EDB does not follow the characteristics of other fuel components, such as BTEX, because BTEX was found in the LNAPL source at FS-12, but no EDB was detected although EDB was found at concentrations above the MCL migrating in the downgradient groundwater. This tends to indicate that the EDB may leach from the source more rapidly than the other fuel components and may not be a continuing source of groundwater contamination as long as the other components; however, the lack of detectable EDB in the LNAPL source may also be due to inability of analytical methods to detect the very low concentrations of EDB remaining in the source that notwithstanding may still leach and continue contaminating groundwater.

The FS-1 extraction and treated water discharge system demonstrates how groundwater extraction and discharge to the surface water can be manipulated for hydraulic control. This system was designed to prevent upwelling of EDB-contaminated groundwater into a local river and cranberry bog. Groundwater was initially extracted at a rate of approximately 750 gpm from four extraction wells and treated before being discharged to the river. The system was optimized to reduce operational requirements and cost while maintaining protection of receptors and hydraulic control by eliminating one of the four extraction wells and reducing the flow to 515 gpm.

The FS-29 plume at MMR demonstrates the need for thorough characterization of the plume. This plume has two lobes with EDB-contaminated groundwater: (1) a shallow plume with an average thickness of 30 feet at starting at approximately 30 feet below msl and extending to approximately 100 feet below msl; and (2) a deeper plume with an thickness ranging from 30 to 50 feet at starting at approximately 120 feet below msl and extending to approximately 220 feet below msl (Jacobs 2000a). Failure to understand the distribution of EDB concentrations and migration characteristics of each of these plumes could have allowed EDB-contaminated groundwater to continue migrating untreated to potential receptors further downgradient. Also,

the migration characteristics and natural attenuation of the EDB contamination is important so that the extraction wells could be placed in optimal locations to capture the highest concentrations of EDB to protect downgradient receptors.

The Del Monte site also includes a groundwater extraction system for both its shallow and basal aquifers. An advantage to the extraction system for the shallow aquifer is that lowers the water table elevation for hydraulic control that (1) helps to reverse local groundwater flow by lowering the water table potentiometric surface to minimize migration of contaminated groundwater from the treatment zone; and (2) helps to lower the water table elevation (the potentiometric surface) to increase the treatment zone for the associated SVE treatment of EDB contamination in the soils as discussed in Section 6.2.3. Extraction of groundwater from the source area in the basal aquifer has been effective at reducing the groundwater with the highest EDB concentrations. This system relies on MNA for downgradient compliance of EDB concentrations in the groundwater as further detailed in Section 6.2.7. A recent five-year review of the Del Monte site found that the extraction system in the basal aquifer in conjunction with natural attenuation may not be adequate return the basal aquifer to productive use because the downgradient groundwater fails to consistently meet the EDB MCL. The extraction and treatment system could be modified as necessary if natural attenuation is found inadequate to meet remediation objectives; additional extraction wells could be installed downgradient and connected to the existing treatment system, which was designed with additional capacity, as necessary to ensure compliance with the MCL.

The Hasting OU6 groundwater extraction system was found to provide effective hydraulic control of the groundwater. A cost benefit of the extraction well network used at OU6 was use of existing wells and in particular a well that was concurrently used to supply industrial non-potable water.

6.2.1.2 Water Treatment Systems

The flexibility of groundwater extraction system to remediate various types and combinations of groundwater contamination is based not on the extraction system but rather on design of the appropriate water treatment systems to use a combination of technologies as necessary to effectively treat each contaminant in the influent received from the extraction wells.

Each of the extracted groundwater treatment systems used at MMR uses GAC. A GAC water treatment system was also used as a wellhead protection remedy for an agricultural water supply well at the Home Oil site (see Section 6.2.6). As noted above, EDB has a lower propensity to adsorb to organic carbon, which is the principle behind GAC treatment. This, however, does not mean that GAC is not adequate to reach the MCL for EDB, but rather that more surface area (i.e., more GAC media) is required to adequately reduce the EDB concentration before discharge. Consequently, the GAC treatment system was designed with adequate capacity based on conservative assumptions of the influent flow rate and maximum EDB concentration.

These assumptions were used in part to size the primary or lead GAC vessel with adequate capacity. The GAC water treatment systems at MMR also include a lag GAC vessel that serves at least two purposes: (1) as a polishing unit to further reduce EDB concentrations providing a more robust system; and (2) as a back-up unit in case the primary or lead GAC unit experiences break-through (i.e., adsorption sites on the GAC media are inadequate to capture enough EDB

molecules to reduce the EDB concentrations below the MCL). These assumptions and GAC system design have provided sufficient water treatment to reduce EDB concentrations below the MCL.

The extraction and treatment system designed for the FS-29 plume at MMR demonstrates the flexibility of this technology in treating multiple contaminants. FS-29 included contribution from other sources that added contaminants to the groundwater with chemical and physical properties different from EDB. The treatment system was designed to remove additional contaminants so that a single remediation system treated multiple sourced plumes rather than requiring multiple systems uniquely treating individual classes of contaminants (e.g., VOCs).

One limitation that requires consideration during design of water effluent from water treatment systems is the geochemistry of the effluent and its suitability for the receiving waters. For instance, MMR discharged GAC-treated water to surface waters, but designed the water discharge system with air-bubblers in the river to increase the dissolved oxygen concentrations necessary for the ecological health of the river.

The water treatment system used for the extracted groundwater from the shallow aquifer at the Del Monte site used an *ex situ* phytoremediation system. This phytoremediation treatment of the groundwater used a closed-loop and lined system collecting water in sumps and re-circulating water through drip irrigation to indigenous trees (the Koa haole plant) that evapotranspired and metabolized the contaminants in the water. A treatability/pilot study was performed before full-scale implementation to determine the effectiveness of this *ex situ* phytoremediation technology. Limitations of this closed-loop system included inadequate capacity during high rain events and high rain periods, so the system was designed to include adequate capacity to reduce potential for overloading the treatment system; re-direction of water to a secondary treatment plant, which was designed for extracted groundwater from the basal aquifer, was also designed to prevent shutdown of the extraction system when the phytoremediation process lacks capacity. Conversely, this larger system required augmented irrigation during drier periods to maintain the plants.

The water treatment system for the extracted groundwater from the basal aquifer at Del Monte used a packed-tower air stripper followed by GAC treatment to polish the water prior to discharge. This system was designed with capacity for expansion of the groundwater extraction system in the basal aquifer if natural attenuation failed to reduce EDB concentrations below the MCL downgradient of the existing extraction area at the source. This system also was designed with additional capacity to treat water from the shallow aquifer when the capacity of the *ex situ* closed-loop phytoremediation treatment was inadequate. These two water treatment systems demonstrate how remediation systems can be developed and designed with foresight to anticipate potential changes and needs.

No separate water treatment was required for the groundwater extraction system at Hastings OU6 because the water was used for multiple industrial purposes in which the water was effectively treated by air stripping. This further reduced costs in addition to the use of an existing well that was already being used to provide industrial non-potable water as described in Section 6.2.1.1. Industrial use of these contaminated extraction waters and the air-stripping

included use as non-contact cooling water in a cooling tower, sluicing of fly and bottom ash from coal-fired steam generating furnaces, and non-contact cooling water for bearing assemblies. The volatile compounds either were air stripped directly, such as the case in the cooling tower, or the water was cycled to an ash pond where the compounds volatilized.

6.2.2 AIR SPARGING/SVE FOR GROUNDWATER TREATMENT

As indicated in Section 6.1, the principle of an AS/SVE system is to actively increase the volatilization of contaminants from groundwater and extract the contaminant-laced soil vapor generated for extraction and *ex situ* treatment to reduce any residual groundwater contamination to concentrations below remedial action objectives (e.g., the MCL for EDB) before the groundwater reaches the receptors. The interception and volatilization of all contaminants in groundwater is virtually impossible, but the objective of this system is to optimize the placement of air injection wells to intercept the highest concentrations in the plume; the rate of air injection must be optimized to avoid potential issues associated with the injection of air, such as creating an effective groundwater flow barrier causing other contaminated groundwater to miss the treatment zone and causing an increase to the groundwater potentiometric surface causing groundwater to flow away from the treatment zone.

The Home Oil site selected AS/SVE as its remedy based on general design criteria for this technology in treating VOCs like EDB, information from preliminary site studies and tests with an initial limited AS/SVE system, and the site specific characteristics, such as the large grain and pore size of the media and the depth to groundwater. It was determined that EDB concentrations across the plume decreased over 90% after about 15 years of operation (McGuire and Wilson 2010). This system was modified by changing the screened interval elevation within the groundwater when the aquifer level did not drop as anticipated and additional extraction wells were installed for the SVE system. Other issues during operation of this system at Home Oil included vibrations from the pumps causing loosening and failure of couplings and implementation/construction/operation challenges because of proximity to structures including the grain silos. This system remains in operation to remediate other petroleum constituents, but EDB concentrations have now achieved MCLs.

Multiple options are available for *ex situ* treatment of extracted contaminated soil vapor depending on the principle contaminants as detailed in Section 6.2.4.

6.2.3 AIR SPARGING/SVE FOR SOURCE TREATMENT

The source for FS-12 at MMR was treated using AS/SVE to eliminate or at least minimize further leaching of EDB contamination into the groundwater plume from the LNAPL and vadose zone. The AS/SVE was implemented to additionally treat the groundwater. The AS component introduced air into the aquifer to volatilize EDB from the groundwater while the SVE system removed the EDB transferred to the soil gas; the SVE system also created a vacuum in the vadose zone to further volatilize EDB from the source to treat the LNAPL and vadose zone contamination (i.e., the source of the groundwater contamination). No other reviewed sites used this remediation technology for source reduction (Table 6-1). The AS/SVE system at FS-12 was part of a time-critical removal action that operated between October 1995 and February 1998. This AS/SVE system was discontinued because it was found that it would not be effective in

addressing the EDB contamination in groundwater that was migrating downgradient outside of the range of the AS/SVE system.

This configuration of AS/SVE, although effective in many situations as demonstrated in the review of other sites summarized in Section 6.2.2, indicates one of the potential detriments of this system. The AS/SVE system may have been effective in treating the EDB contamination both in the local groundwater and the source itself, but it has limitations that must be addressed in the design:

- It provides ineffective hydraulic control of the groundwater;
- It may actually create a hydraulic divide in the groundwater causing increased migration of contaminated groundwater away from the injection zone (i.e., the injected air causes an increase in the water table elevation);
- It provides only localized treatment, so contaminants that have migrated past the treatment zone must rely on natural attenuation processes for reduction in contaminant concentrations;
- It injects air driving up dissolved oxygen concentrations in groundwater, which are beneficial for aerobic biodegradation processes important for petroleum constituents such as BTEX, but the elevated dissolved oxygen concentrations depress the rate at which anaerobic biodegradation occurs for EDB (i.e., reductive dehalogenation); and
- SVE may reduce moisture levels in the soil depressing biodegradation rates in the soils.

LNAPL was discovered in 1996 during site characterization of the Home Oil site. Consequently, an AS/SVE system was also used at the Home Oil site to treat the EDB source in the LNAPL and vadose zone in addition to treating the groundwater as discussed in Section 6.2.2. It was determined in 2010 after about 15 years of operation that the free phase product plume decreased in total volume and EDB levels in groundwater decreased over 90% (McGuire and Wilson 2010). As indicated in Section 6.2.2, EDB concentrations in groundwater now achieve MCLs and so it seems that the AS/SVE remediation system was effective in eliminating or reducing residual EDB in the remaining petroleum source to eliminate the risk from EDB in the groundwater.

The Del Monte site also uses SVE to treat residual EDB contamination in the vadose zone and the capillary fringe of the shallow aquifer. The SVE system is optimized to treat the capillary fringe at the interface of the aquifer and the vadose zone by including groundwater extraction to depress the water table elevation (the groundwater extraction system for Del Monte is reviewed in Section 6.2.1.1).

The full scale SVE system used for source removal in the soils at Hastings OU6 was based on previous pilot test in a similar EDB source area. This SVE system at the source at OU6 was found to effectively treat the source after approximately three years of operation, although it was operated for an additional two years. This system was calculated to remove approximately 422 pounds of EDB from the soil during its operation from 1997 until 2002 based on effluent concentrations in the soil gas recovered by the SVE system (USEPA 2007b, USEPA 2012b).

6.2.4 SVE AIR TREATMENT

Exhaust (i.e., the air to be emitted to the atmosphere) from the SVE system typically must be treated to remove contaminants prior to release to the atmosphere. As indicated in Section 1.2.2, vapor-phase EDB will be degraded in the atmosphere by reaction with photochemically-produced hydroxyl radicals with a half-life estimated to be 64 days; EDB is not expected to undergo direct photolysis in the ambient atmosphere. Consequently, some treatment is required to avoid transferring groundwater contamination to atmospheric contamination.

The SVE system used at MMR for EDB source reduction found that catalytic oxidation (cat-ox) treatment of the air discharge from the SVE was inadequate by itself to remove the EDB. Consequently, the air discharge from the cat-ox unit was further scrubbed by a GAC unit as a polishing unit. The SVE gases at Del Monte are effectively treated using only GAC units.

6.2.5 BIOAUGMENTATION/BIOSTIMULATION

The only site that used bioaugmentation (also referred to as biostimulation and enhanced bioremediation) is the Hasting OU6 site where an electron donor (carbon) substrate amendment was injected to encourage the native microbes in the groundwater. A treatability study was first performed at OU6 to determine whether the groundwater was amenable to bioremediation. The treatability study did indicate that the aquifer characteristics were conducive to reductive dehalogenation with appropriate geochemistry characteristics; also, the aquifer was found to have favorable characteristics for injection of substrate, such as homogeneity, high transmissivity, and a low groundwater gradient. An appropriate electron donor substrate was selected that could adsorb to soils without significantly decreasing water flow through the soil while creating a long-lasting treatment zone. This substrate was diluted as appropriate and also mixed with sodium bicarbonate to increase the pH (i.e., reduce the acidity) of the water caused by an upgradient landfill to optimize conditions for reductive dehalogenation.

This bioaugmentation was completed in 2010, so limited data are available to assess the effectiveness. The time estimated for the bioaugmented groundwater to flow to the downgradient monitoring wells is two years and several rounds of sampling will be required to assess trends to associate the treatment with reducing concentrations of EDB and other indicators of reductive dehalogenation, such as changes to the redox potential of the groundwater. It is believed based on the treatability study and preliminary data that the bioaugmentation will be effective at reducing EDB concentrations (Gresham 2011a).

6.2.6 WELLHEAD PROTECTION

Wellhead protection includes treatments directly at the water supply well used for receptors. Wellhead protection can also include abandonment of the water supply well and substitution with another water supply well in an uncontaminated area, such as was done at the Home Oil site for one of the water supply wells for the town of Seldon. The Home Oil site also discovered an agricultural-use water supply well contaminated with EDB, so a GAC system was installed as wellhead protection (see Section 6.2.1.2 for a general discussion of GAC water treatment for EDB contamination).

MMR added wellhead protection as a preliminary precaution early in its investigation of FS-28 prior to construction of its time-critical removal action to ensure that receptors were not potentially exposed to EDB in the water supply. This wellhead protection remained as part of the time-critical and the non-time critical removal actions in addition to its extraction and treatment system to ensure that receptors were not potentially exposed to EDB in the water supply. Remediation systems are designed for installation and operation and are optimized periodically to make adjustments with the objective of intercepting contaminated groundwater prior to its migration to a receptor. However, uncertainty remains with any designed system because of the uncertainty about data completeness and interpretation of those data used to characterize the site and to predict contaminant fate and transport at the site. Consequently, the MMR wellhead protection demonstrates that it can be implemented as an effective final defense to treat the supplied water prior to exposure of the receptor.

6.2.7 MONITORED NATURAL ATTENUATION

Remediation of the basal aquifer at the Del Monte site relies on a groundwater extraction system as described in Section 6.2.1.1 to reduce EDB source concentrations to levels at which natural attenuation processes can further reduce EDB concentrations to levels below the federal MCL of 0.05 µg/L. Natural attenuation processes include biodegradation; dispersion; dilution; sorption; volatilization; radioactive decay; and chemical or biological stabilization, transformation, or other destruction of contaminants of contamination (USEPA 1999). Monitoring of natural attenuation can include evaluation by statistical trending analysis of contaminant concentrations over extended periods of time, evaluation of natural attenuation capacity in the aquifer and potential changes in natural attenuation by measurements of aquifer geochemistry, monitoring and evaluation of the contaminant plume for changes in concentrations and groundwater flow, numerical modeling of the groundwater flow and contaminant concentrations, and/or more elaborate evaluation of biodegradation and abiotic processes using compound-specific isotope analysis (USEPA 2004, USEPA 2008c).

Del Monte has a long-term monitoring program for groundwater sampling and evaluation of natural attenuation capacity in the basal aquifer. A recent five-year review, however, indicates that the EDB MCL criterion is not consistently met (USEPA 2010b). As noted in Section 6.2.1.1, the groundwater extraction system was designed with additional treatment capacity to expand the system to improve performance to meet the EDB MCLs.

6.2.8 SOURCE EXCAVATION

Source excavation is mechanical removal of the contaminated soil to be treated and backfilled at the site or transported for offsite treatment as necessary and disposal at an appropriately permitted landfill (i.e., based on the waste characteristics). The Del Monte site excavated approximately 2,000 tons of EDB-contaminated soil from one spill area and an additional 16,000 tons of EDB-contaminated soil from a former pesticide mixing and storage area. In this case, the excavated soil was spread on a nearby field for landfarming and passive air stripping of the volatile compound from the soil. This technique physically removes the source of the groundwater contamination to eliminate further contribution to the contaminant plume. Although this technique is effective, it requires that all contaminated soil be removed that is above a specific criterion for the contaminant based on its ability to leach to groundwater.

Otherwise, residual contamination in soil can continue to leach to the groundwater. At Del Monte, an impermeable cap was later installed to mitigate leaching of residual EDB contamination from soil (see Section 6.2.9).

6.2.9 LOW PERMEABILITY CAP

As indicated in Section 6.2.8, removal of the EDB source in the soil at the Del Monte site was found inadequate to prevent leaching of residual EDB to the groundwater. An impermeable or low permeability cap can be useful in reducing the infiltration rate of surface waters and precipitation to minimize the amount of water percolating through the vadose zone and leaching contaminants from the residual source. An impermeable cap can take many forms, including a layer of low permeability clay (e.g., hydraulic conductivity less than 1.0×10^{-7} cm/sec), structure, a parking lot, or as in the case of Del Monte a designed densely vegetated pad to evapotranspire moisture from the soil. Low permeability caps typically include storm/surface water diversion and control to minimize water infiltrating in the area, which was included at the Del Monte site.

Low permeability caps can also be useful in conjunction with SVE and bioventing systems to prevent short-circuiting directly between the extraction screen and the surface and can also help increase the ROI for these systems. Although the Del Monte site included SVE, no indications were found that the vegetation cap provided an adequately impermeable cap to soil gas to increase the efficiency and radius of influence for the soil vapor extraction wells.

6.3 CONCLUSIONS

All remediation technologies have general design requirements, constraints, and limitations based on inherent properties of each technology that must be considered in evaluating and designing remediation system using technologies in various configurations appropriate for specific site conditions. The remediation systems from MMR, Home Oil, Del Monte, and Hastings OU6 demonstrate how a system can be designed from multiple remediation technologies, installed, operated, and optimized throughout its lifecycle to effectively treat EDB contamination (see Section 6.2). Figure 6-1 depicts the general overall lifecycle from site characterization through remediation design/construction and site remediation for the four sites included in this report. The following sections briefly summarize the benefits and limitations for the various remediation technologies in meeting the general corrective measures evaluation criteria on a comparative basis.

6.3.1 OVERALL PROTECTION OF HUMAN HEALTH AND THE ENVIRONMENT

Remediation of the EDB contamination at each of the four sites has been effective in protecting HHE. It was noted for MMR, as an example, that community concerns historically have questioned the protectiveness, but data indicate that EDB concentrations continue to decline and that receptors at the exposure points are being adequately protected. MMR included a wellhead protection system at the source of the community water supply well potentially affected to ensure this protection and added bubblers to infuse air into the discharge increasing dissolved oxygen concentrations in the effluent to improve wildlife habitat. Consequently, remediation systems at the sites have been designed, optimized, and evolved as necessary to ensure protection of HHE

Figure 6-1. EDB Remediation Timelines (Page 1 of 3)

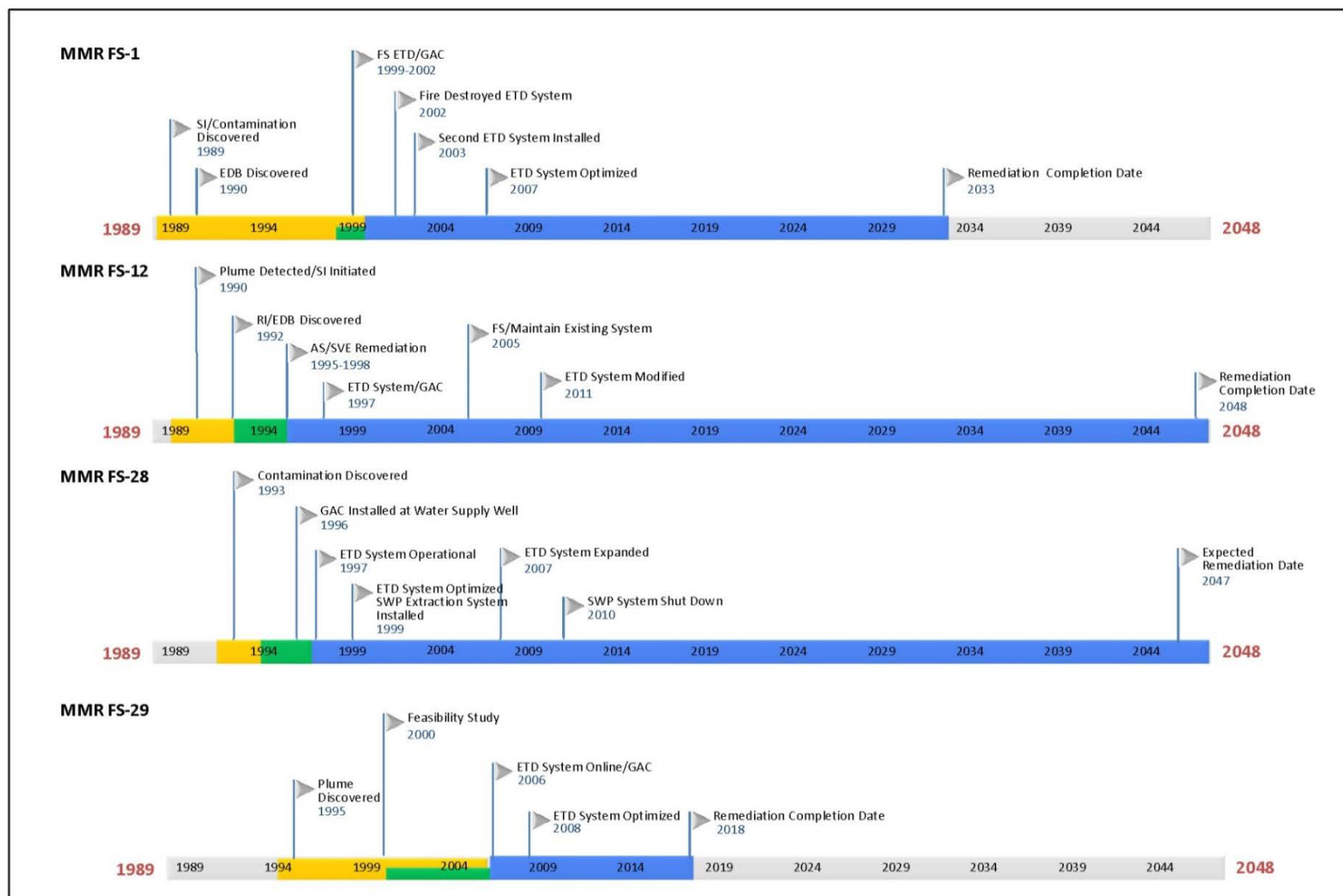


Figure 6-1. EDB Remediation Timelines (Page 2 of 3)

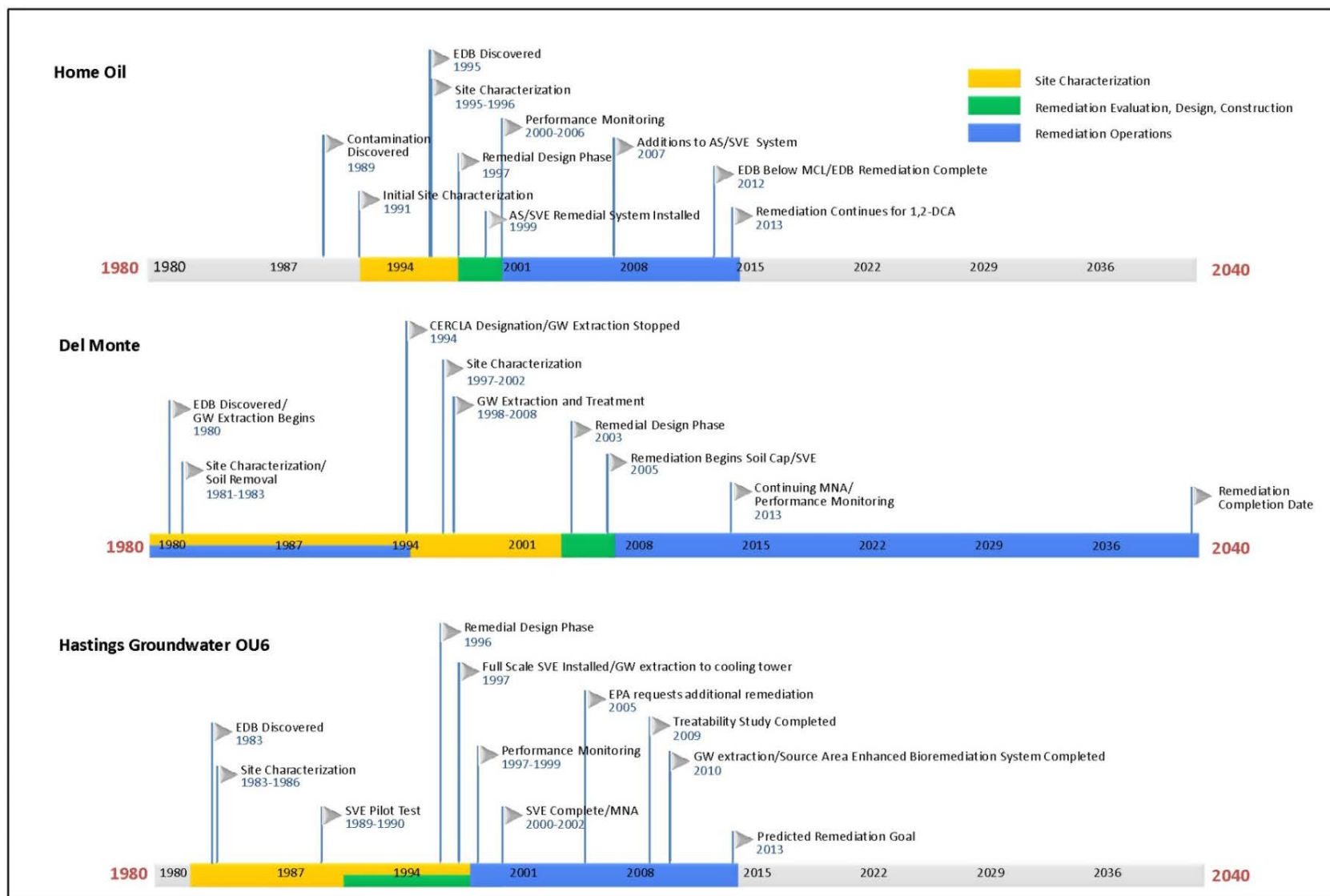


Figure 6-1. EDB Remediation Timelines (Page 3 of 3)



6.3.2 ACHIEVEMENT OF CLEANUP OBJECTIVES

As indicated in Section 6.3.1, the reviewed remediation systems at the four sites have been developed and operated to ensure achievement of cleanup objectives for EDB, which is the federal MCL (0.05 µg/L) or a more restrictive state MCL (e.g., MMCL of 0.02 µg/L). Sometimes expansion of the remediation system is necessary as the plume characteristics change and the EDB continues to migrate and naturally attenuate, such as in the case of the Home Oil site where the AS/SVE system is being extended to ensure adequate treatment.

6.3.3 REMEDIATION TO REDUCE/ELIMINATE FURTHER RELEASE

Source removal is a principle in all groundwater remediation to reduce the duration that the remediation system operates. Source removal, or at least reduction, both reduces costs and the time until protection of HHE is ensured. Source removal or treatment can, however, be complicated by several factors, such as accessibility to the source for either physical removal or treatment.

The Del Monte site demonstrated source removal of EDB contamination in the soils by physically excavating as much of the contaminated soil as possible as well as source removal from the basal (deep) aquifer through a groundwater extraction and treatment system. However, Del Monte still required later to cap the source area where soil was excavated to mitigate leaching of EDB from residual soil contamination (i.e., the remaining source) into the shallow aquifer. Also, the most recent five-year review of the system indicated that natural attenuation of the groundwater in the basal aquifer might not be adequate to be protective of HHE, so the groundwater source removal may require expansion. These subsequent adjustments to the remediation system indicates that source removal must be thorough to effectively reduce the source for protection of HHE and that source removal alone may not be adequate remediation.

6.3.4 LONG-TERM EFFECTIVENESS

Each of the remediation systems evaluated in this report will be effective at protecting HHE in the long-term. Each system removes the contaminant from the groundwater or degrades the contaminant in the groundwater to benign compounds. The groundwater extraction and treatment systems at MMR, Del Monte, and Hasting OU6 each treat the extracted groundwater to remove the EDB (and other contaminants as necessary) before discharging the treated water either to surface waters or re-injected to the aquifer. Similarly, the SVE systems at all of the sites extract contaminants from source or from air sparging of the groundwater and treat the air effluent prior to discharge to the atmosphere. Consequently, each alternative implemented at the four sites provides long-term effectiveness as designed.

6.3.5 SHORT-TERM EFFECTIVENESS

Short-term effectiveness is the evaluation during the time that the remediation system is active and before the remedy is considered complete. The evaluation includes protection of HHE as well as evaluation of risks to workers installing and providing O&M and other risks (e.g., the risk from transportation associated with servicing the system or waste streams). This can be a substantial evaluation for long duration remediation over several decades, such as can be the case for remediation of EDB in groundwater as demonstrated by the several decades predicted for remediation of the plumes at MMR. Several remediation systems and the alternatives selected

require more than a decade to complete treatment for final protection of HHE. Options, such as wellhead protection, have been implemented to protect the receptor pending completion of remediation. MMR provided wellhead protection for a water supply well so that the receptor was protected while the site characterization and remediation proceeded. Home Oil implemented this for short-term protection of both an agricultural supply well and a community supply well; the Home Oil site initially provided drinking water from local stores until the wellhead protection system could be installed. Sometimes, as in the case at Home Oil and at Del Monte, an alternative community water supply well can be installed in an uncontaminated area to provide short-term protection pending completion of remediation.

6.3.6 TOXICITY, MOBILITY, AND VOLUME REDUCTION

Each of the remediation systems evaluated in this report treat the groundwater in some regard, either actively as in the case of groundwater extraction and AS/SVE or passively as in the case of MNA. Consequently, each is effective in reducing toxicity and volume of the contaminants while removing the contaminants to reduce further toxicity, mobility, and the volume of the contaminated plume itself.

6.3.7 IMPLEMENTABILITY

Each of the remediation technologies use well established design, construction, and O&M techniques and use readily available standard equipment and supplies. Certain primary challenges must be evaluated during the planning and design phase to ensure that the remediation system can be readily constructed:

- ETD/ETR
 - The characteristics of the plume distribution must be well understood to install the extraction well screened interval at the proper invert elevation within the aquifer to capture the heart of the plume;
 - The groundwater and contaminant migration must also be well understood to ensure that downgradient receptors are protected;
 - Treatment systems must be serviceable to allow maintenance without interrupting treatment, such as the parallel GAC treatment trains with on in standby at MMR that allow one treatment train to be offline without interrupting groundwater extraction;
 - Structures can prevent access to optimal locations for extraction wells; and
 - Discharge to surface waters or re-injection of treated water requires permits that must be coordinated.
- Air Sparge
 - Again, the groundwater contamination distribution and migration must be understood to properly install injection wells at the appropriate screened depth to be most effective; and
 - Excessive air injection can change groundwater flows (e.g., injected air can minimize local groundwater flow and may increase water table elevations causing

contaminated groundwater to flow away from the treatment zone. Pulsing of different injection wells across the system is often used to mitigate these issues.

- Injection of air can increase DO, which can be beneficial for downgradient aerobic degradation (e.g., for further degradation of residual BTEX) but can impede anaerobic reductive dehalogenation processes for residual EDB.
- Contaminated soil gas migration, such as into surrounding buildings, must be mitigated, such as by the use of SVE.
- SVE
 - The system requires coarse-grained and permeable media to optimize removal of volatile compounds;
 - Extraction of soil vapor is maximized with limited water in the soil pore space because the water can reduce movement of soil vapor;
 - The source being treated must be deep enough to prevent direct communication between the soil vapor extraction well and the surface (i.e., short-circuiting) or other engineering features must be designed to increase the ROI, such as an impermeable pad on the ground surface; and
 - The air treatment system requires air permits that must be coordinated prior to installation.
- Bioaugmentation
 - The ROI can be limited for injections of substrates;
 - Geochemistry of the aquifer must be controlled to optimize conditions;
 - Structures can prevent access to optimal locations for injection of biostimulant substrates (e.g., EVO); and
 - Contaminant concentration rebound after treatment should be anticipated.
- Monitored Natural Attenuation
 - Adequate monitoring wells in appropriate locations and screened to the appropriate depths within the aquifer must be available.
 - Seasonal fluctuations and other changes in groundwater flow must be understood to adequately evaluate temporal contaminant and geochemical trends.
 - Specific natural attenuation processes potentially responsible for contaminant concentration trends can be difficult to identify and quantify.

6.3.8 COSTS

The cost for design, construction, and O&M/optimization of the systems evaluated at the four sites reviewed in this report may not necessarily be a fair comparative analysis because many variables between the sites cause the cost comparison to be unequal. For instance, multiple large spills at MMR that will take many years to achieve cleanup and decommissioning of the systems

will have much higher costs than those for a more localized plume at the Home Oil site. Also, some sites have limited cost information.

In general, however, it can be concluded that ETD/ETR systems typically have much higher total costs because of the energy requirements to pump water from depth, which increases substantially with the depth to groundwater and the size of the plume (e.g., a dispersed relatively low concentration plume, such as many EDB contaminated plumes in which EDB has migrated substantially) will require more extraction wells and pumping than a discrete high-concentration plume (e.g., if EDB/BTEX/MTBE is intercepted shortly after its release before it diffuses and disperses). The high relative cost of extraction, treatment, and re-injection is demonstrated by the cost projected for MMR of approximately \$107M, although this relative cost must be considered in context of multiple plume treatment across a large area from a substantial release over years.

Remediation systems with less energy requirements and reduced O&M, such as AS/SVE systems, such as that used at Home Oil with a cost to-date of less than \$1M, and bioaugmentation as used at Hastings OU6, typically have more low to moderate-range costs. Other more passive remediation systems, such as MNA, have substantially lower relative costs.

6.3.9 COMMUNITY AND OTHER REGULATORY AGENCY ACCEPTANCE

Each of the evaluated remediation alternatives reviewed at the four sites ultimately met with community and regulatory acceptance. However, community relations can change over the course of the site characterization and remediation system selection and implementation process and community involvement and attitudes can vary widely by community. Typically, communities respond more favorably to active remediation systems and wellhead protection programs than to passive systems, such as MNA and caps.

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7.0 REFERENCES

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Appendix A: Maps for the Massachusetts Military Reserve Site

Appendix B: Maps for the Del Monte Site

Appendix C: Maps for the Hastings OU 6 Site

Appendix D: General Information for Air Sparging Technology

Appendix E: General Information for Soil Vapor Extraction Technology

Appendix F: General Information for Reductive Dehalogenation

Appendix G: General Information for Groundwater Extraction and Treatment Technology

Appendix H: General Information for Monitored Natural Attenuation